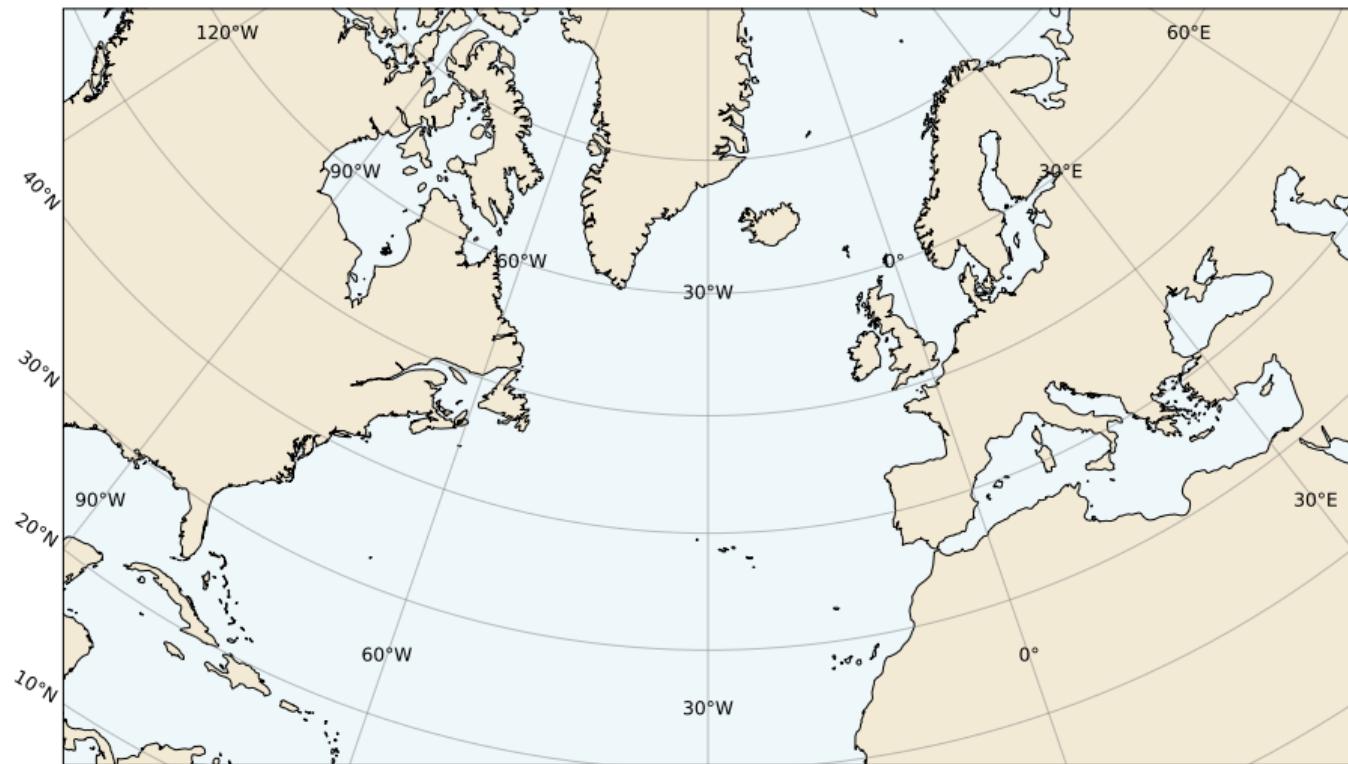


Rossby Wellen

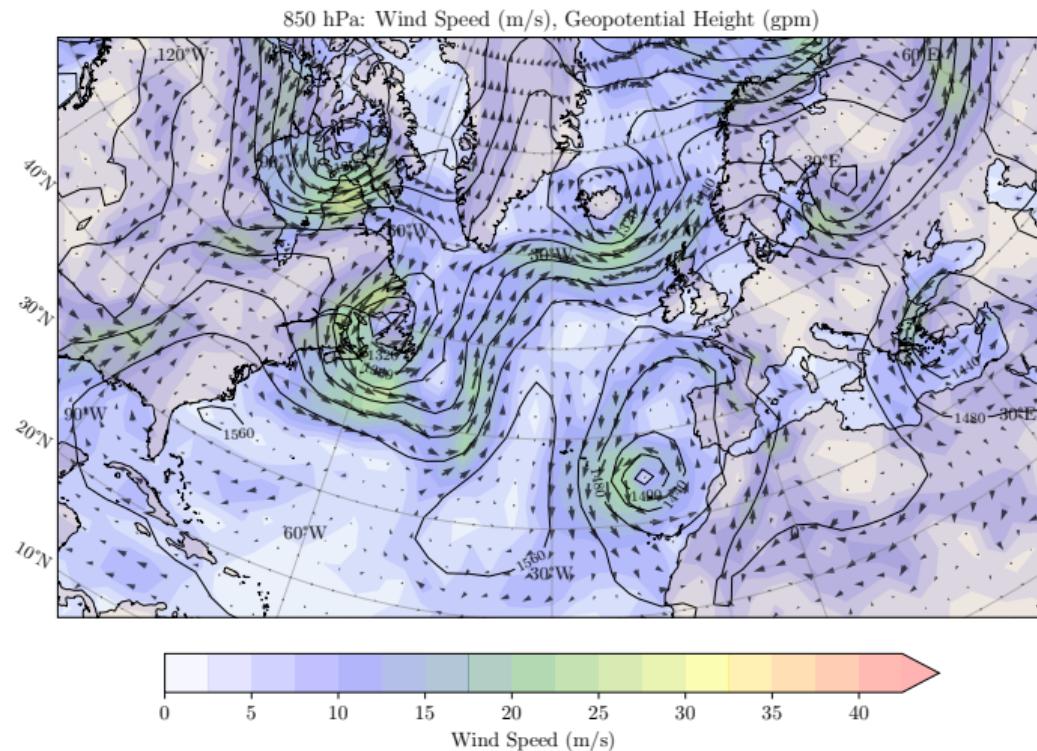
Michael Schmid

June 6, 2025

Karte



Forecast: 01-May-2025 at 00:00, Level 850 hPa

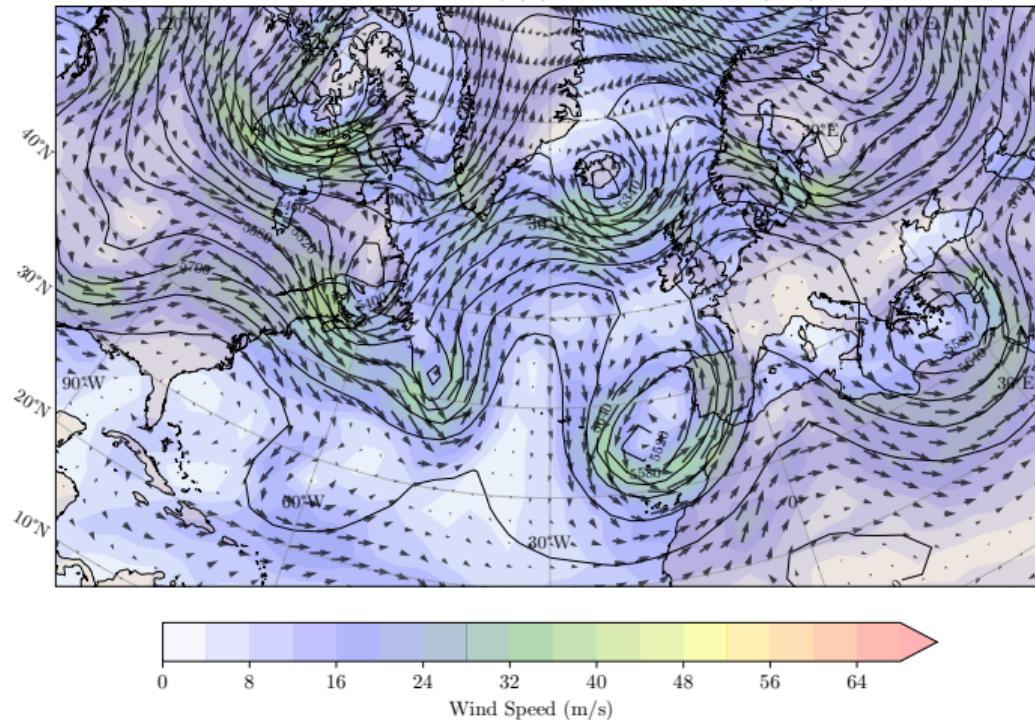


ERA5-Analyse: Jetstream am Mai 2025

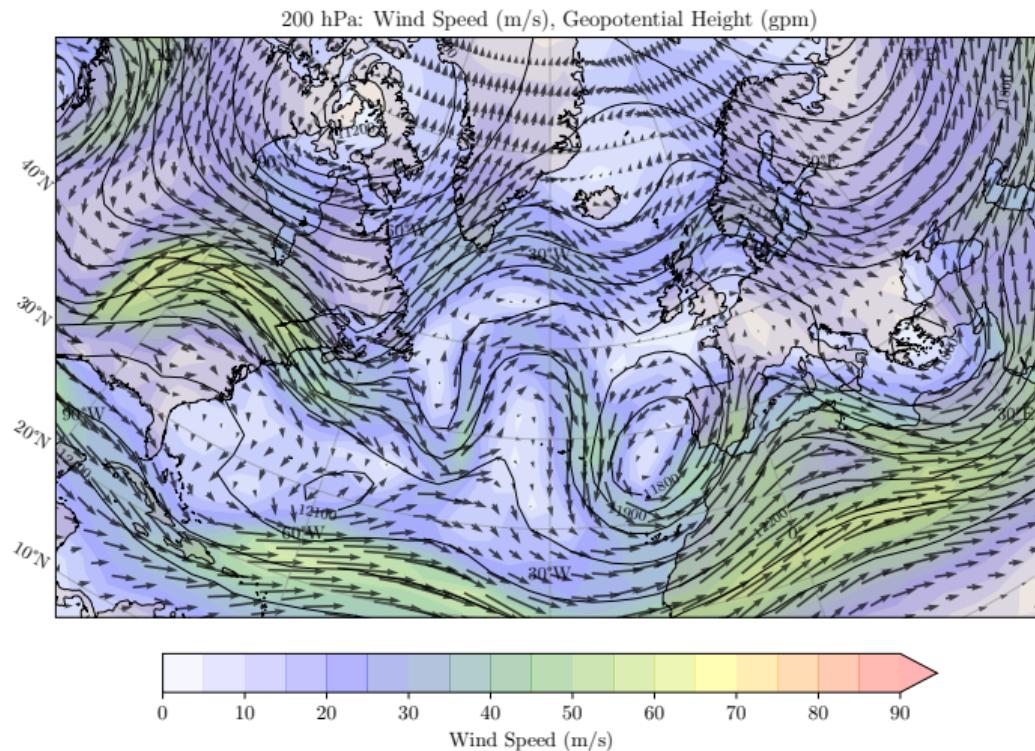
- Datenquelle: **ERA5 Reanalysis** (ECMWF) via CDS API
- Abfrageparameter:
 - Druckniveau: **500 hPa** (obere Troposphäre, Jetstream-Niveau)
 - Variablen: Geopotential, u - und v -Windkomponente
- Visualisierung:
 - Farbkarte: Windgeschwindigkeit (m/s)
 - Linien: Geopotentielle Höhe (gpm)
 - Pfeile: Windvektoren

Forecast: 01-May-2025 at 00:00, Level 500 hPa

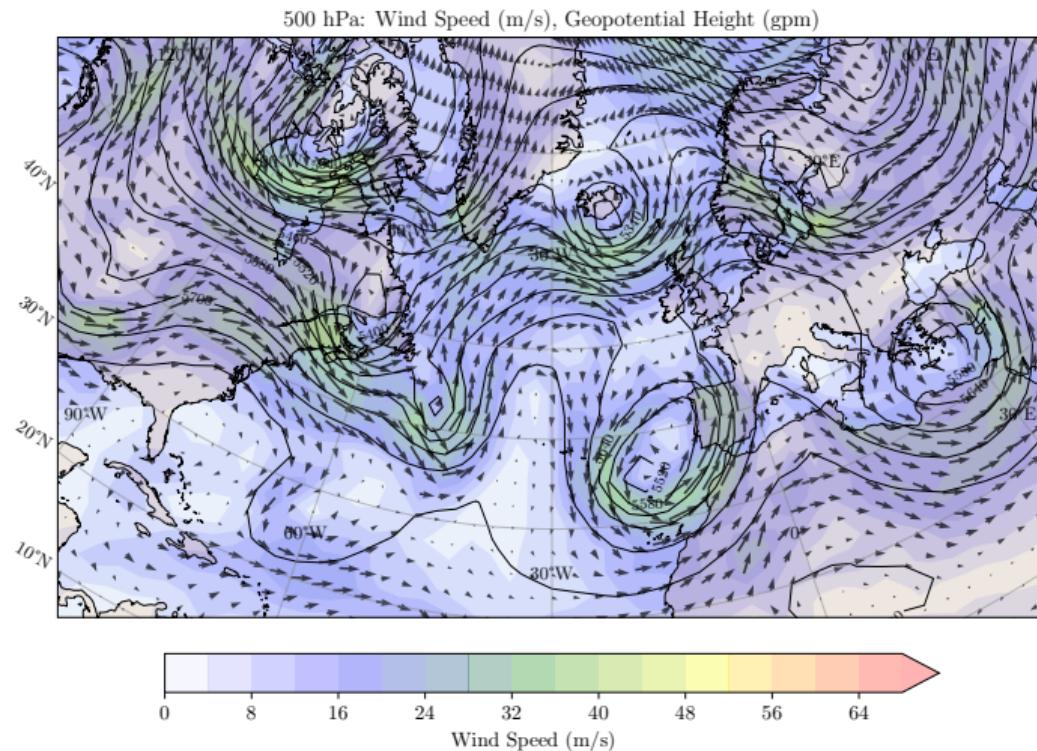
500 hPa: Wind Speed (m/s), Geopotential Height (gpm)



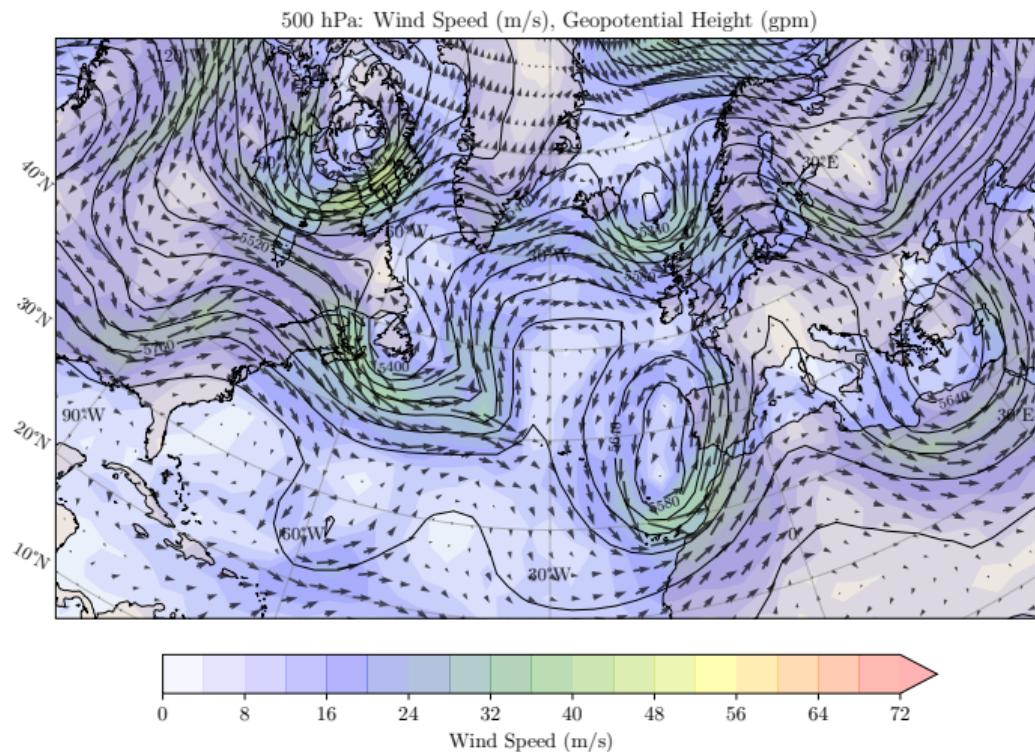
Forecast: 01-May-2025 at 00:00, Level 200 hPa



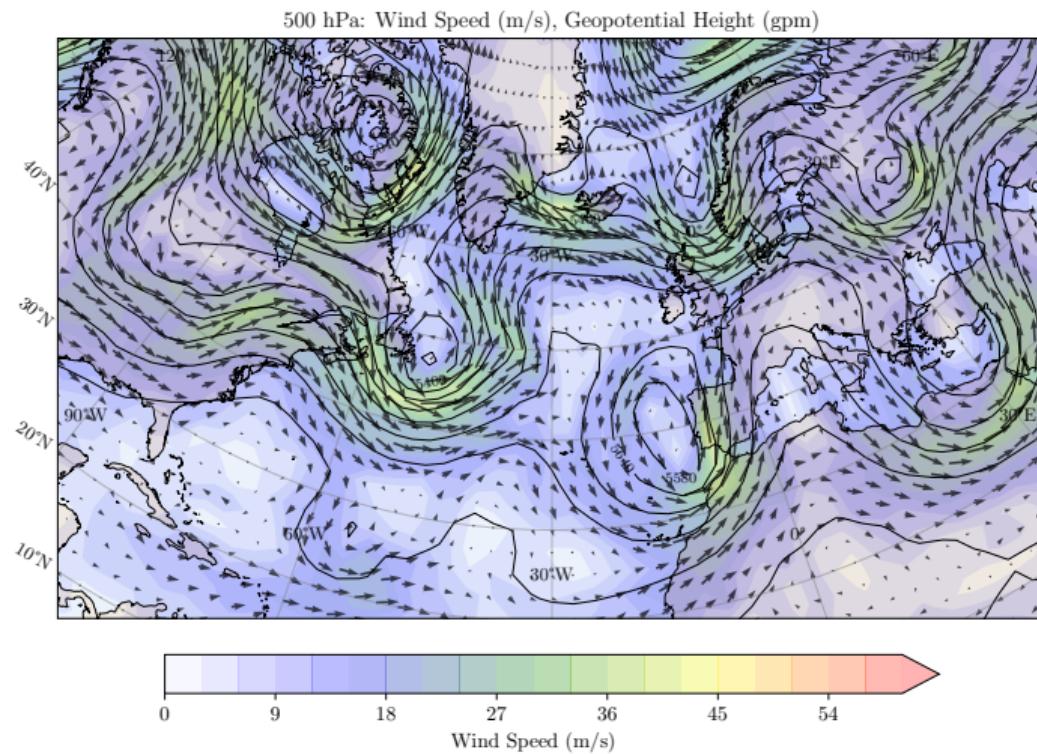
Forecast: 1-May-2025 at 00:00, Level 500hPa



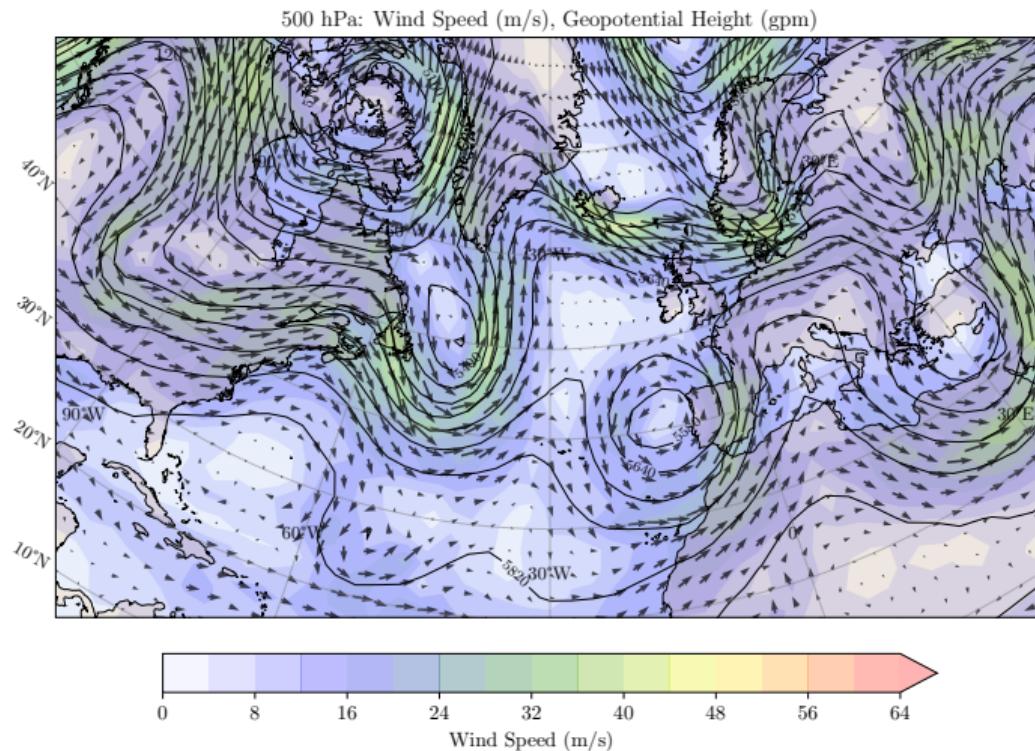
Forecast: 1-May-2025 at 12:00, Level 500hPa



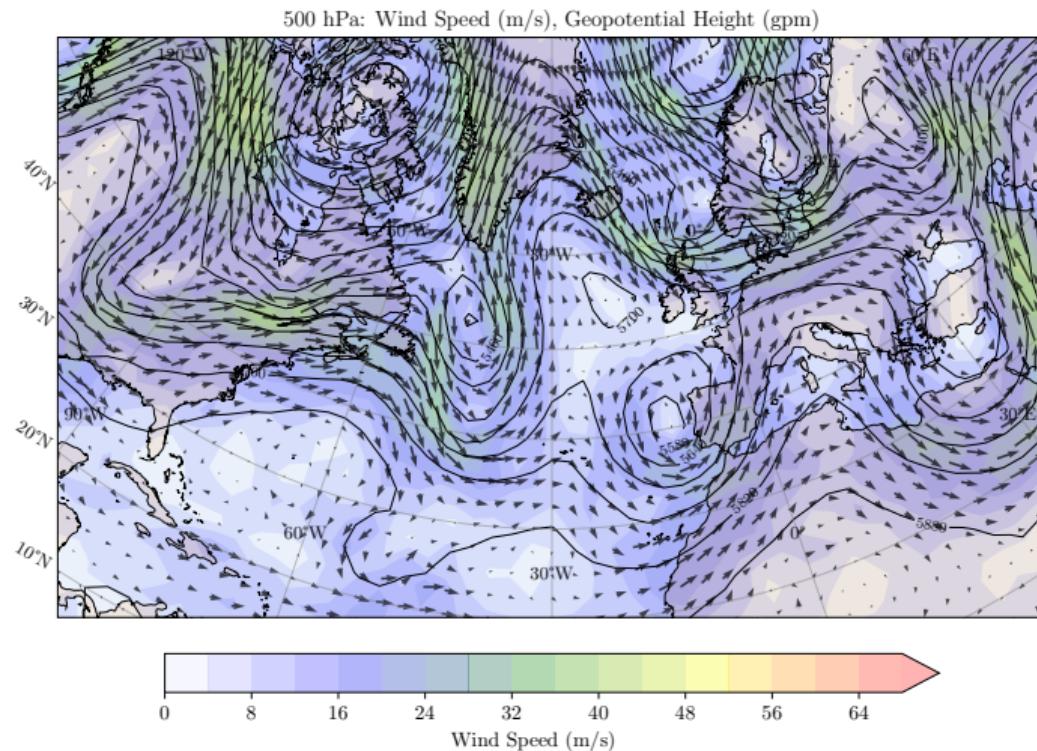
Forecast: 2-May-2025 at 00:00, Level 500hPa



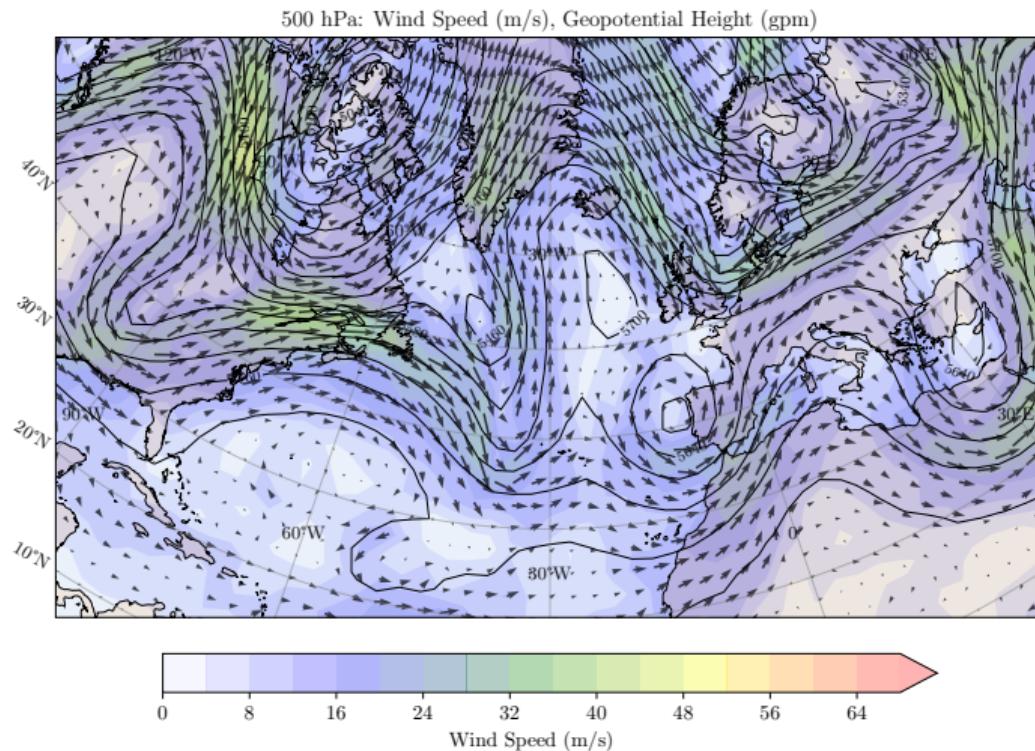
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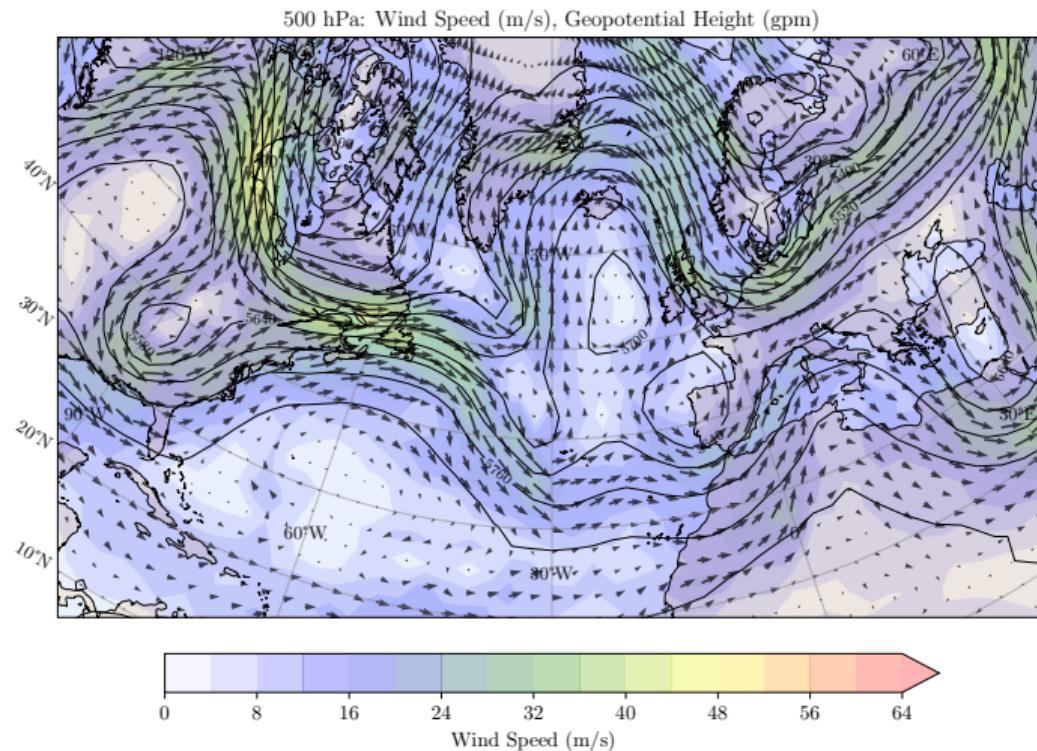
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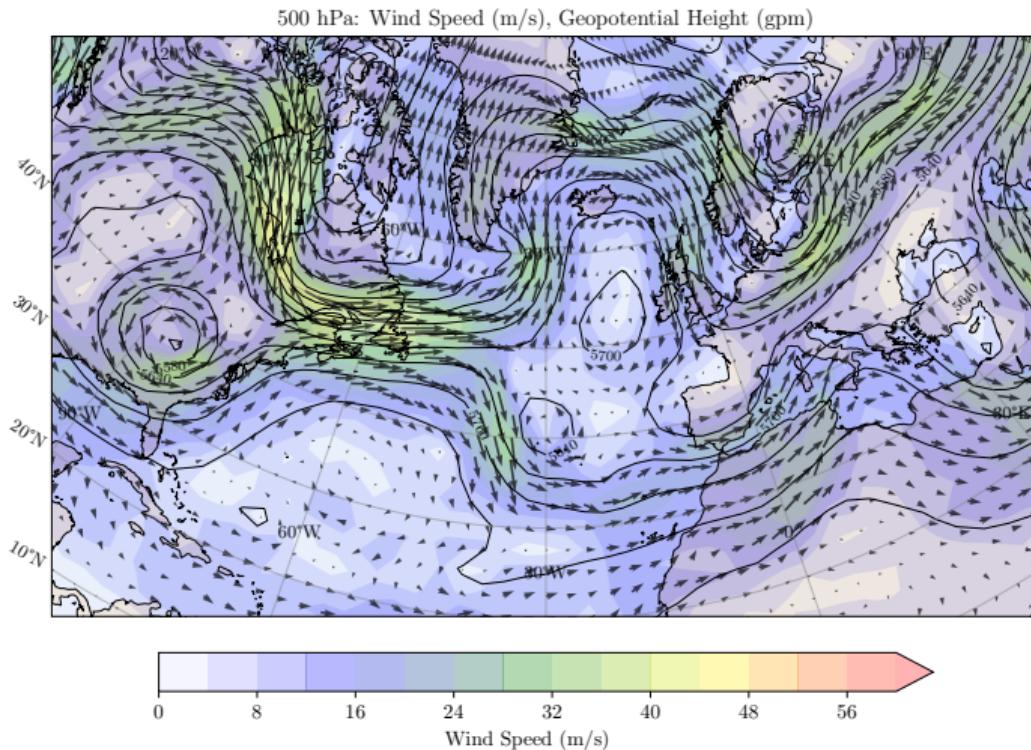
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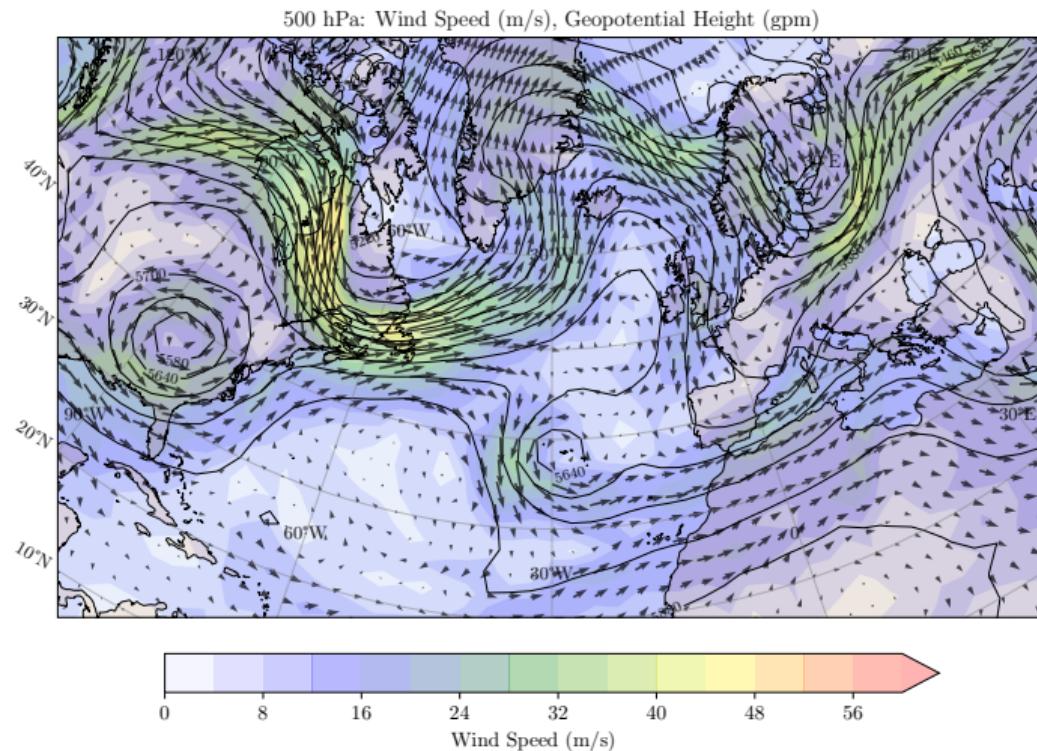
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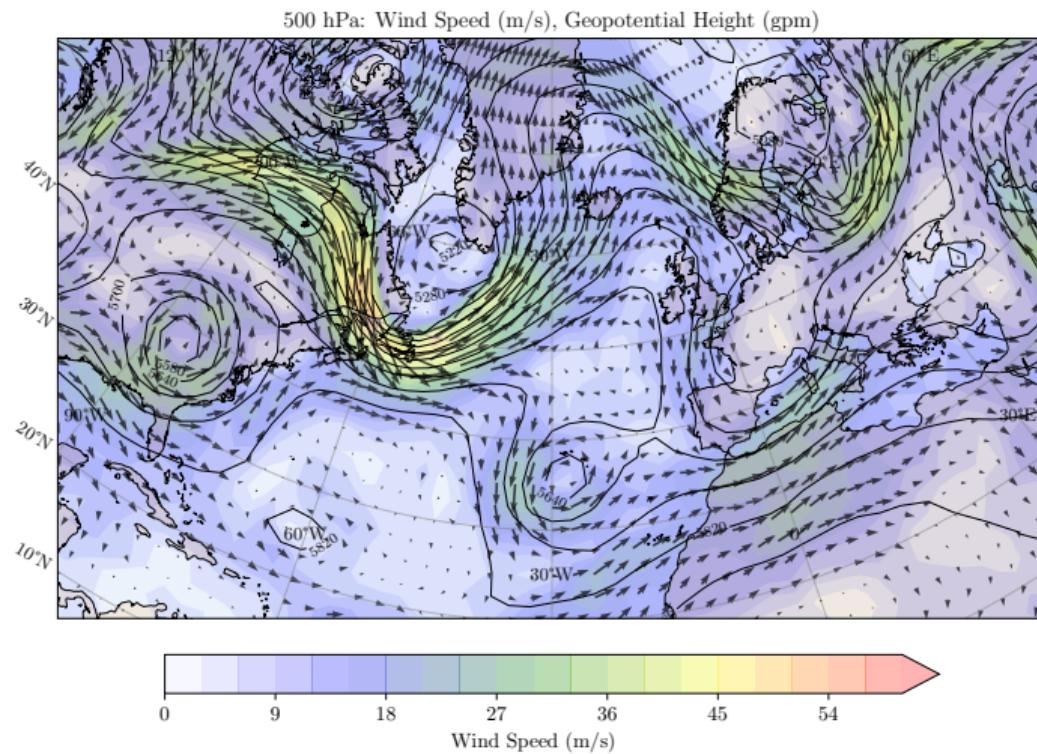
Forecast: 4-May-2025 at 12:00, Level 500hPa



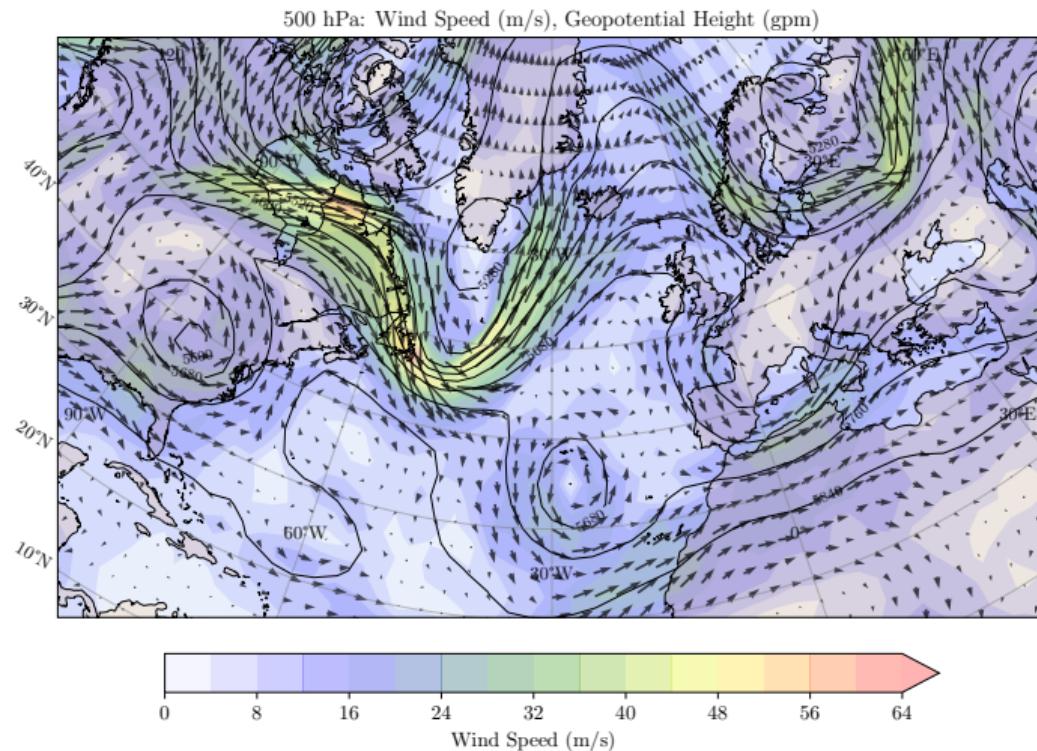
Forecast: 5-May-2025 at 00:00, Level 500hPa



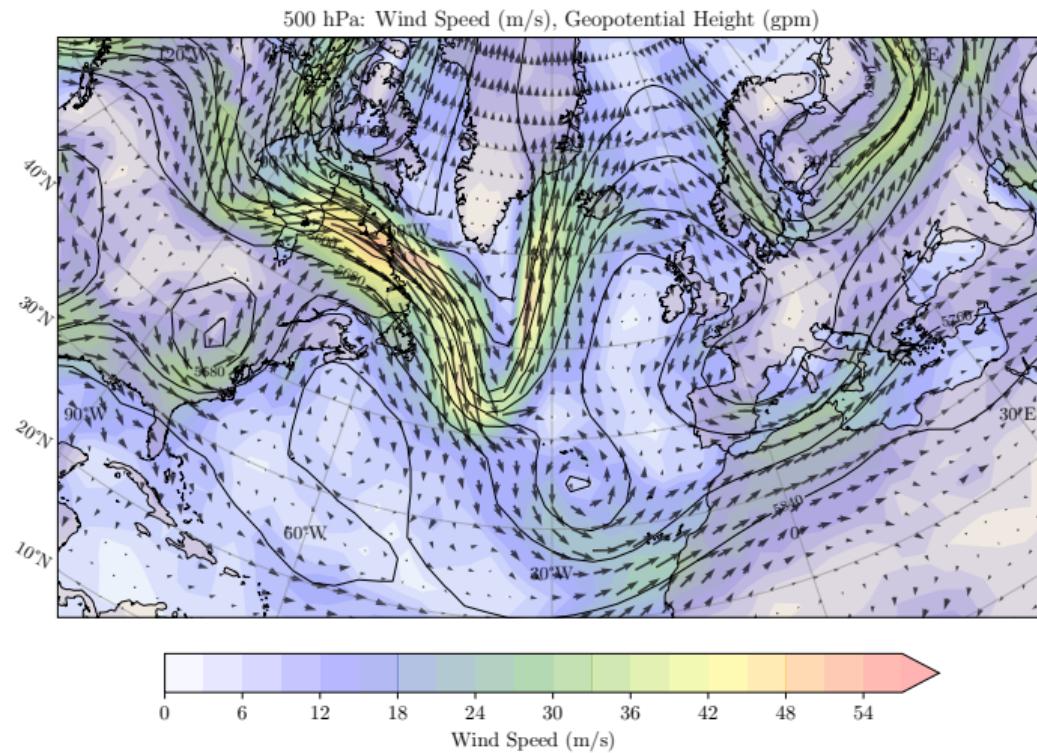
Forecast: 5-May-2025 at 12:00, Level 500hPa



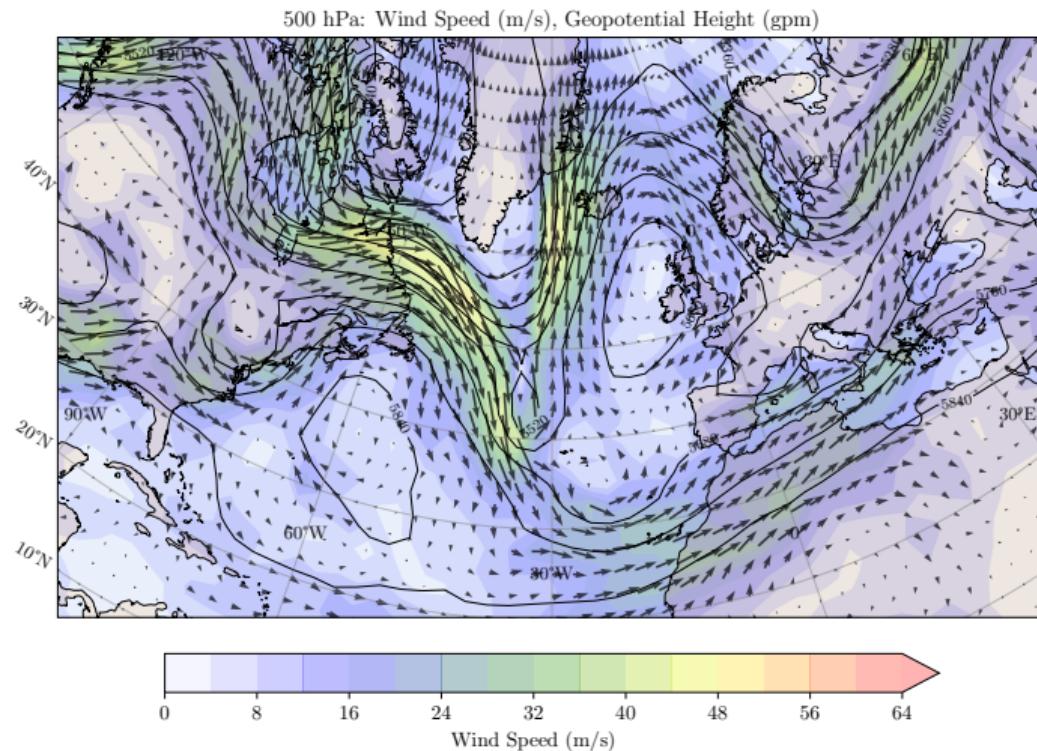
Forecast: 6-May-2025 at 00:00, Level 500hPa



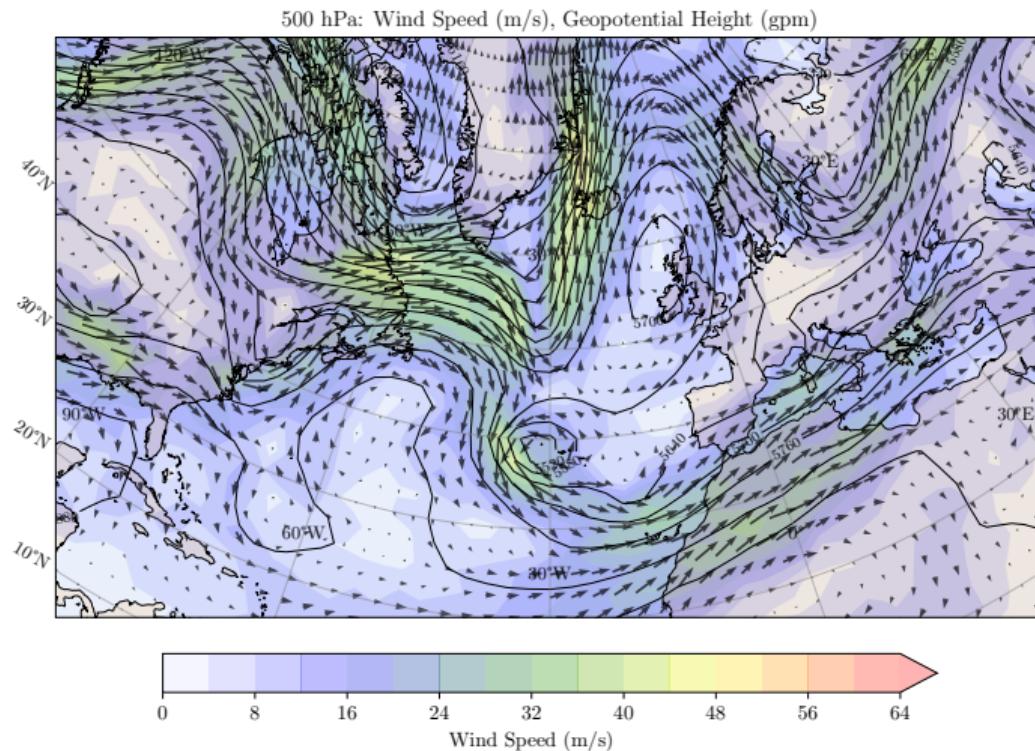
Forecast: 6-May-2025 at 12:00, Level 500hPa



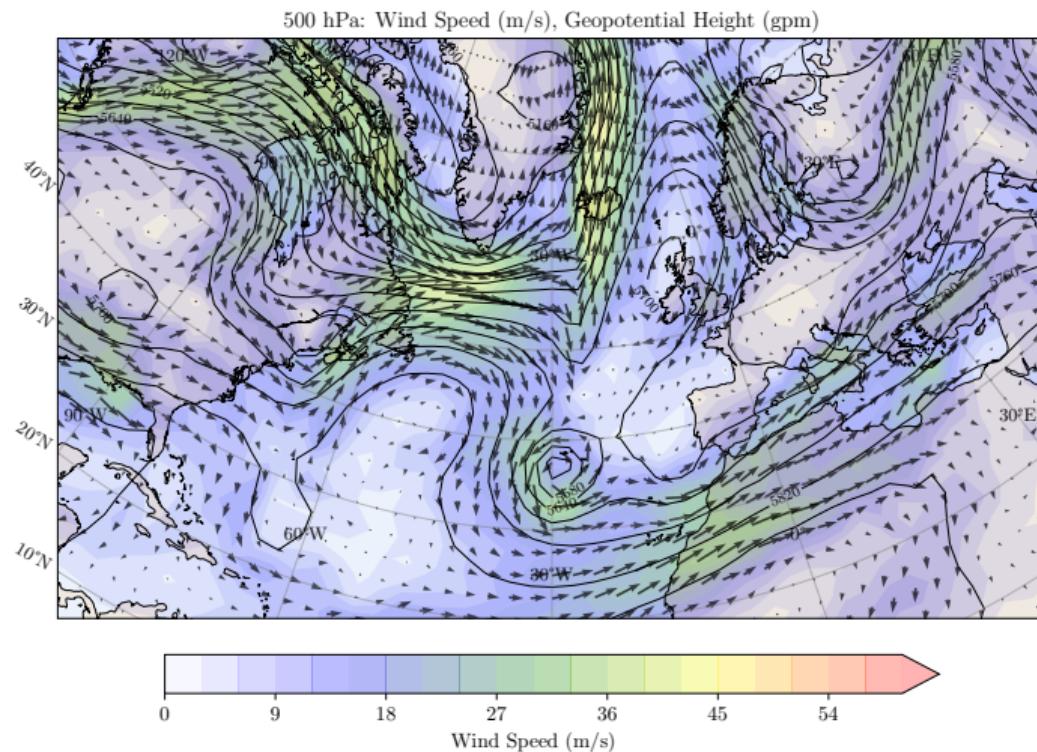
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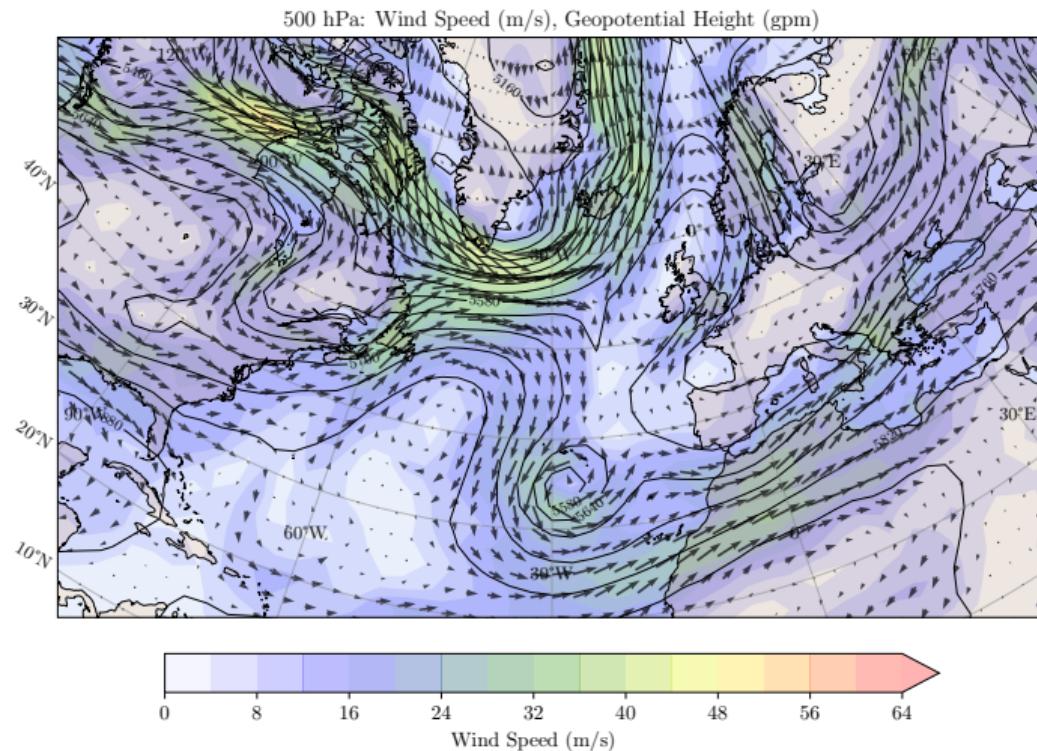
Forecast: 7-May-2025 at 12:00, Level 500hPa



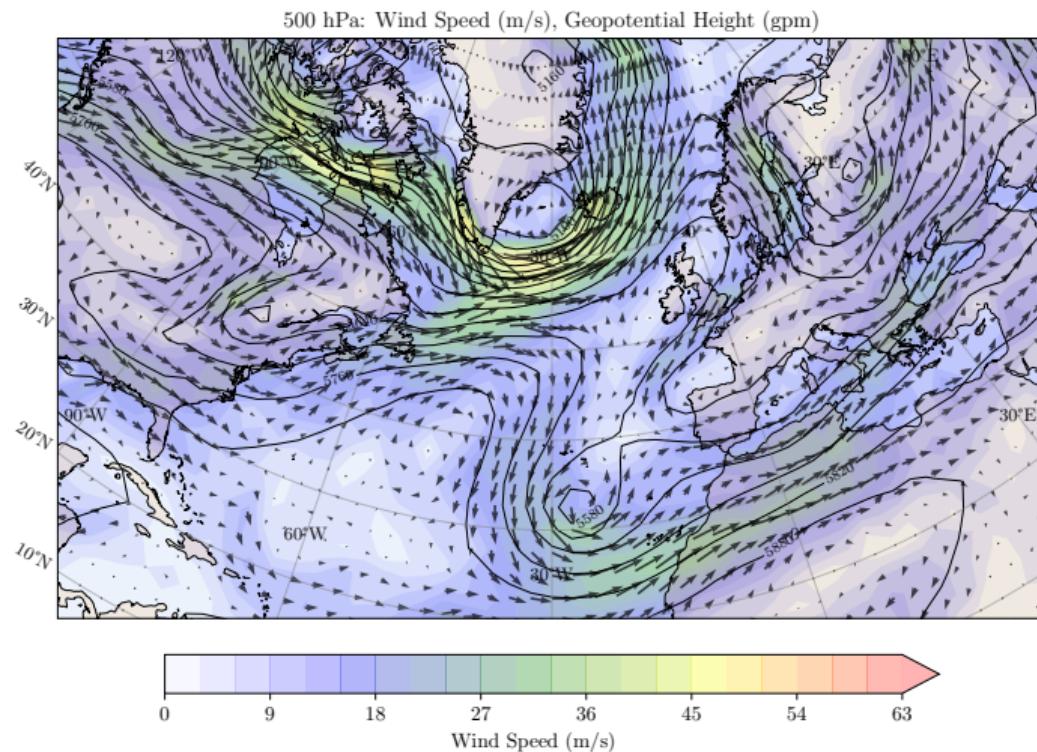
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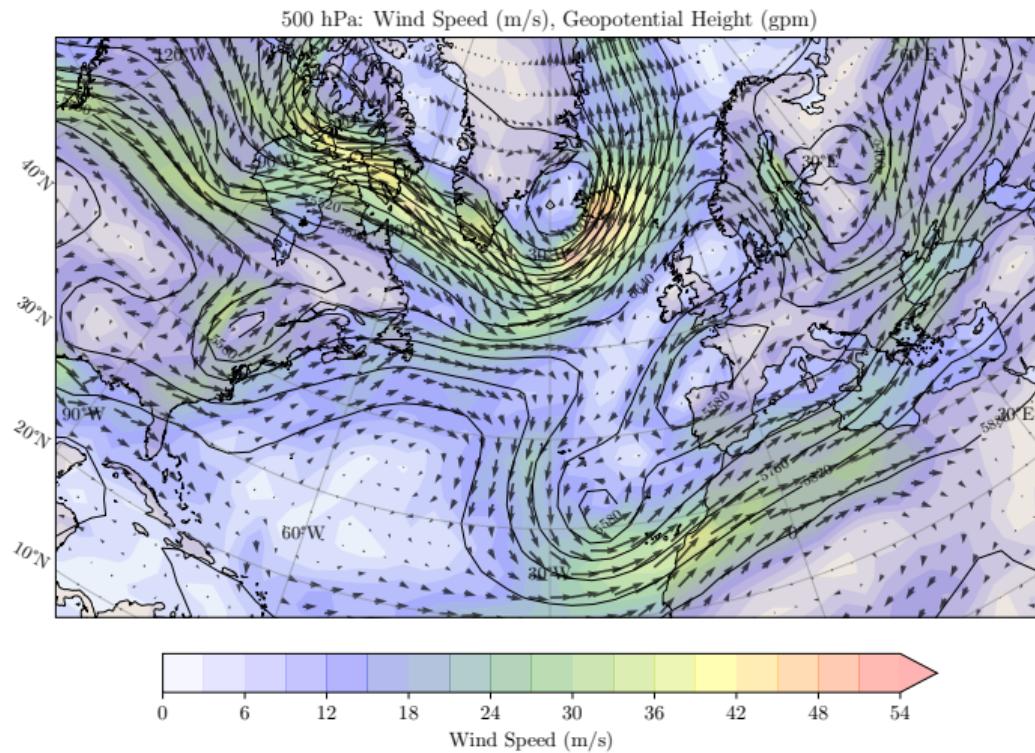
Forecast: 8-May-2025 at 12:00, Level 500hPa



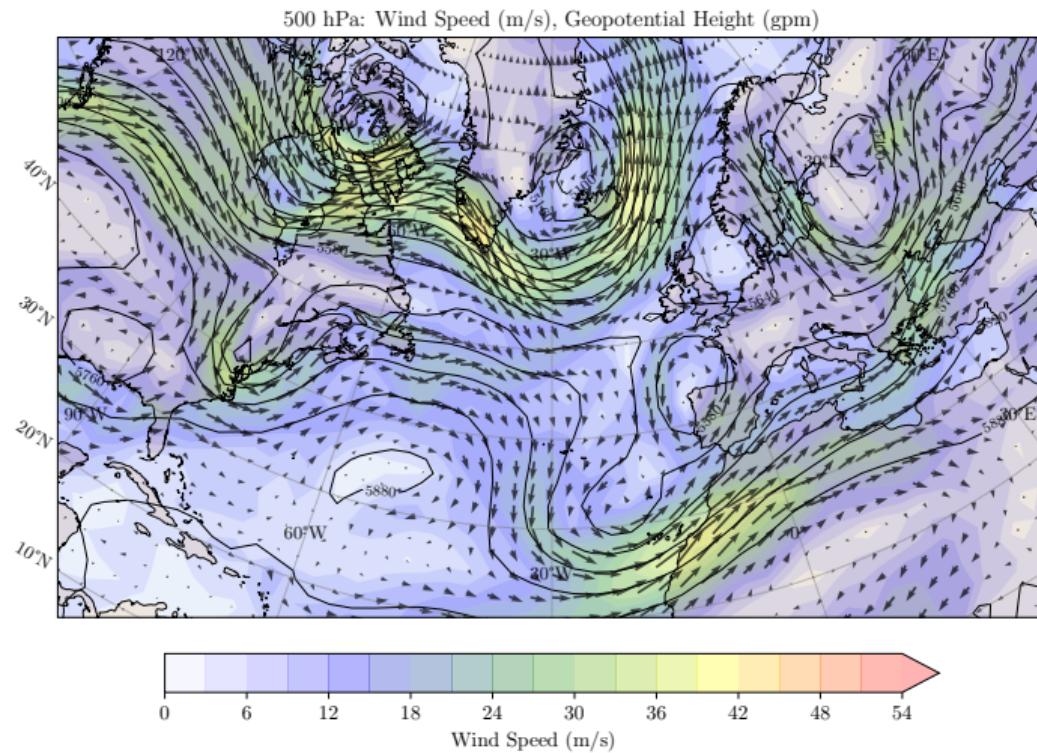
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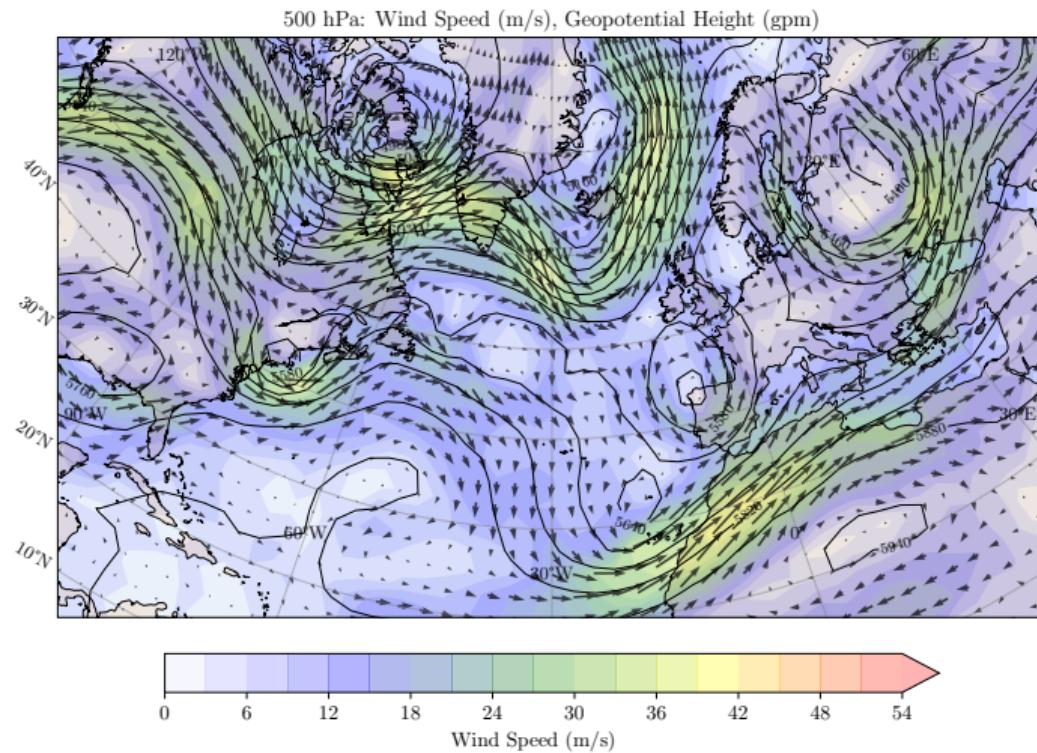
Forecast: 9-May-2025 at 12:00, Level 500hPa



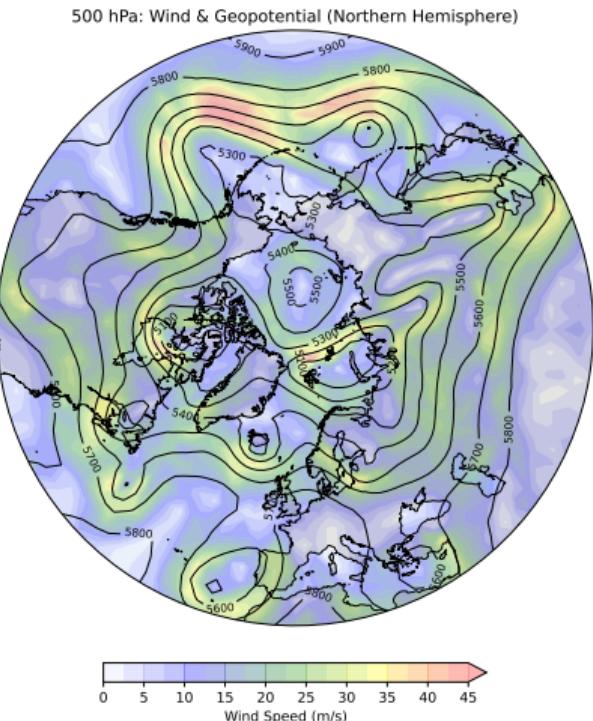
Forecast: 10-May-2025 at 00:00, Level 500hPa



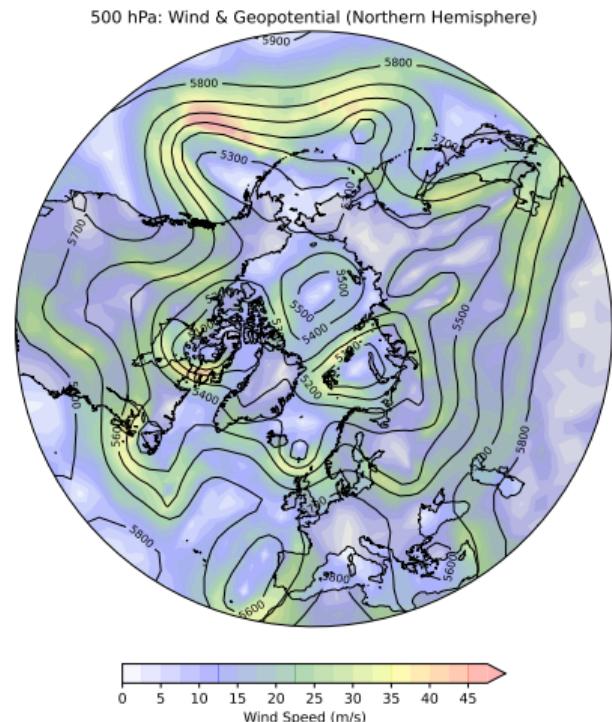
Forecast: 10-May-2025 at 12:00, Level 500hPa



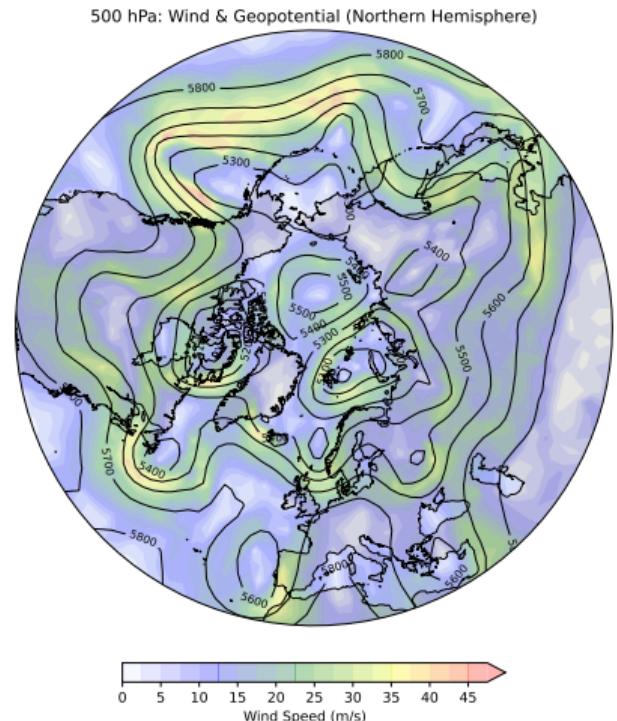
Forecast: 1-May-2025 at 00:00, Level 500hPa



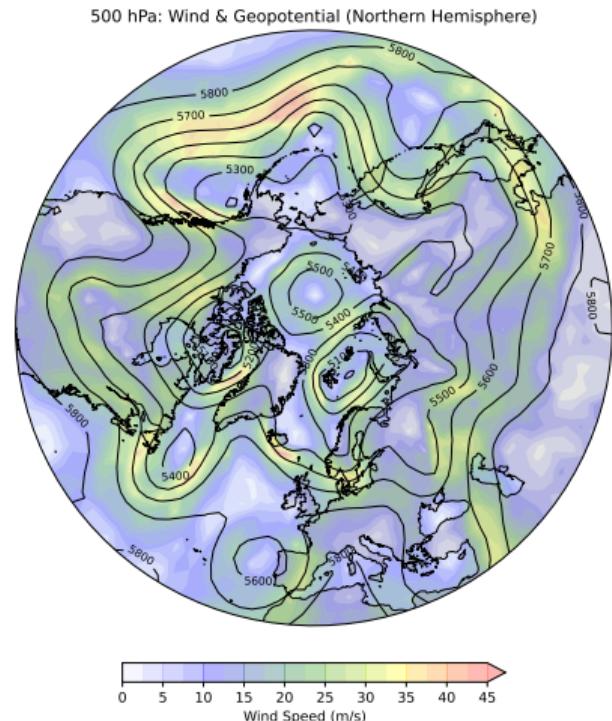
Forecast: 1-May-2025 at 12:00, Level 500hPa



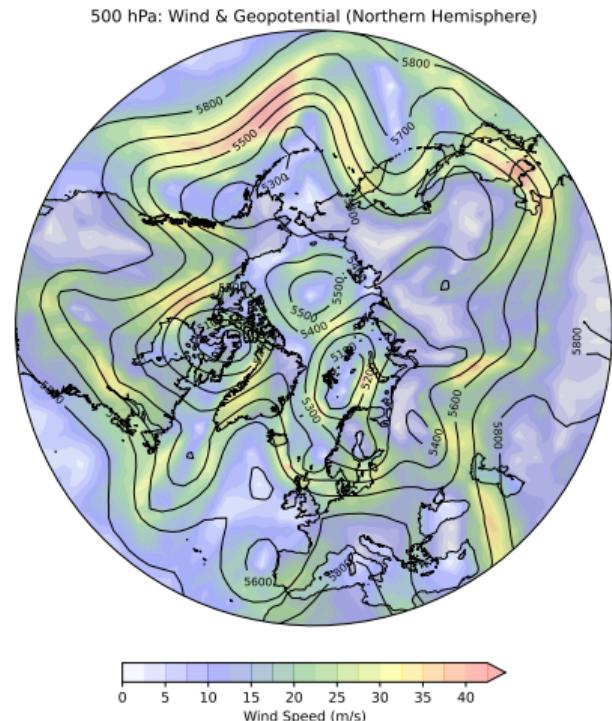
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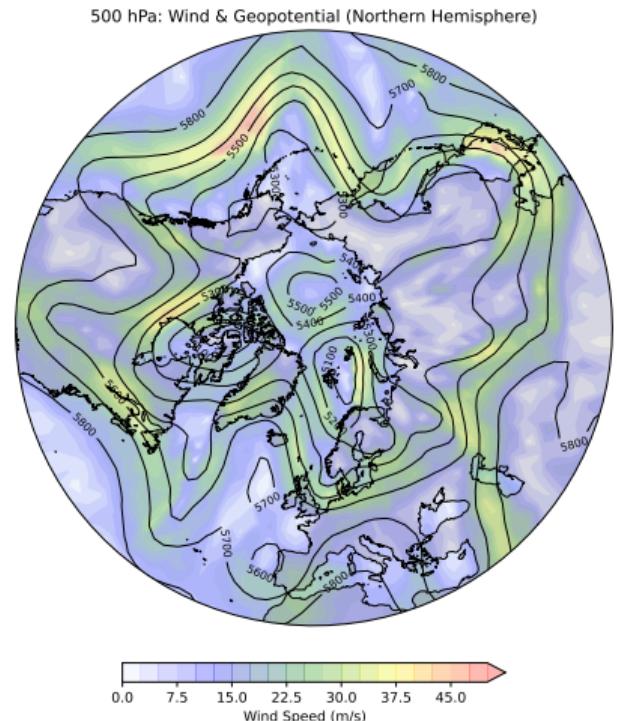
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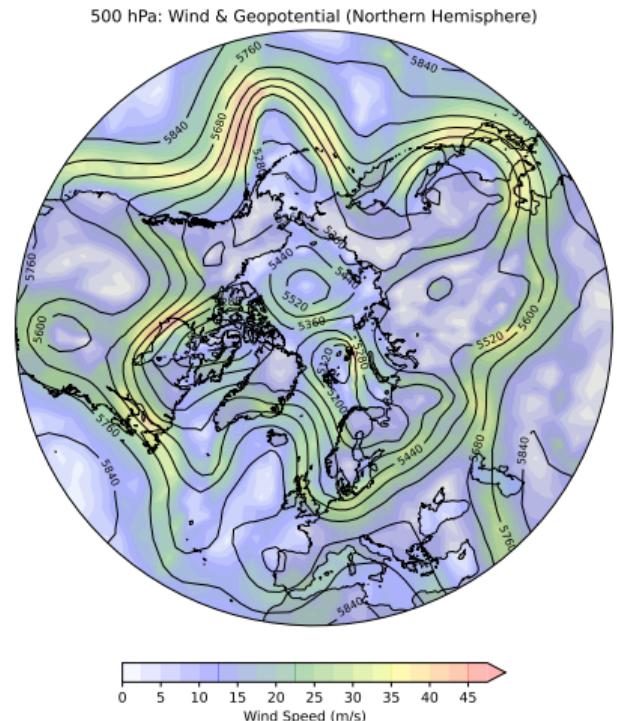
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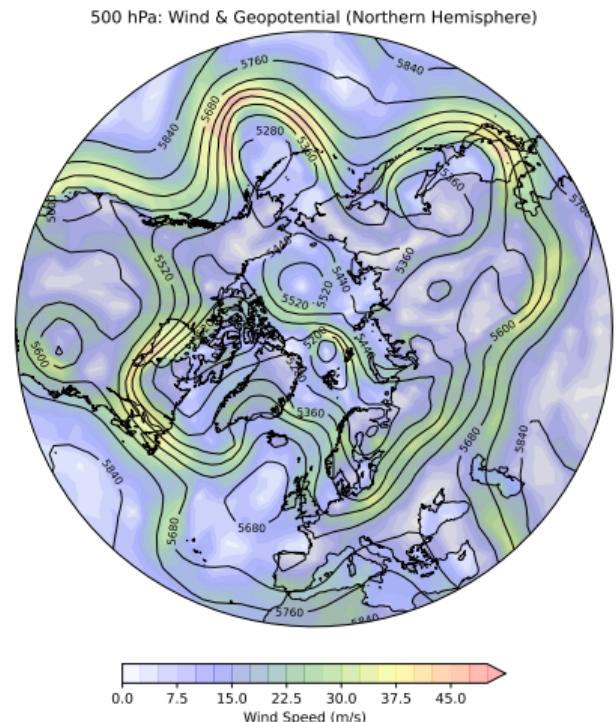
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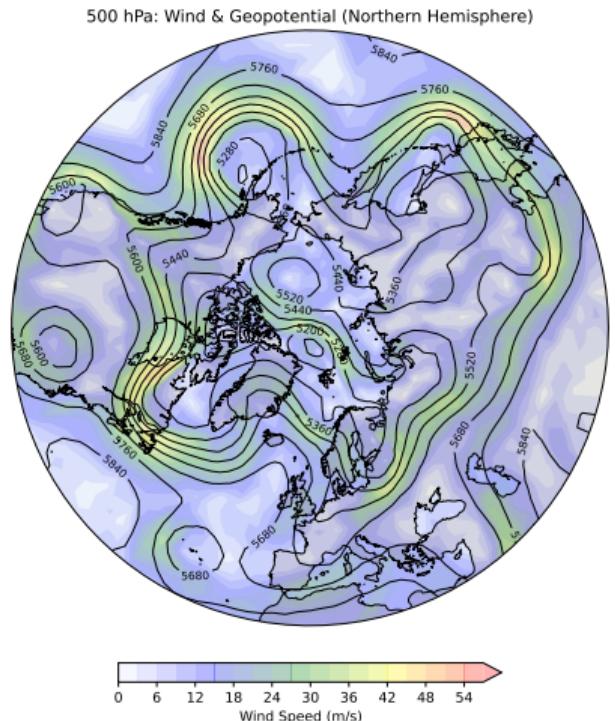
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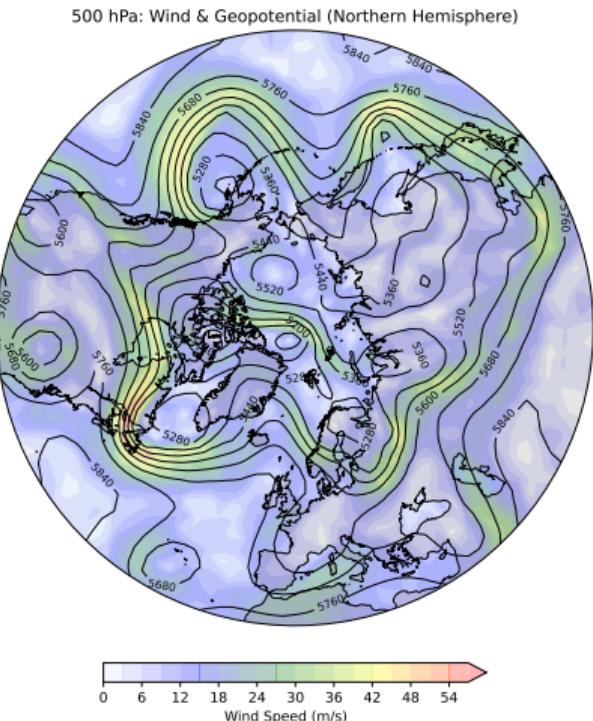
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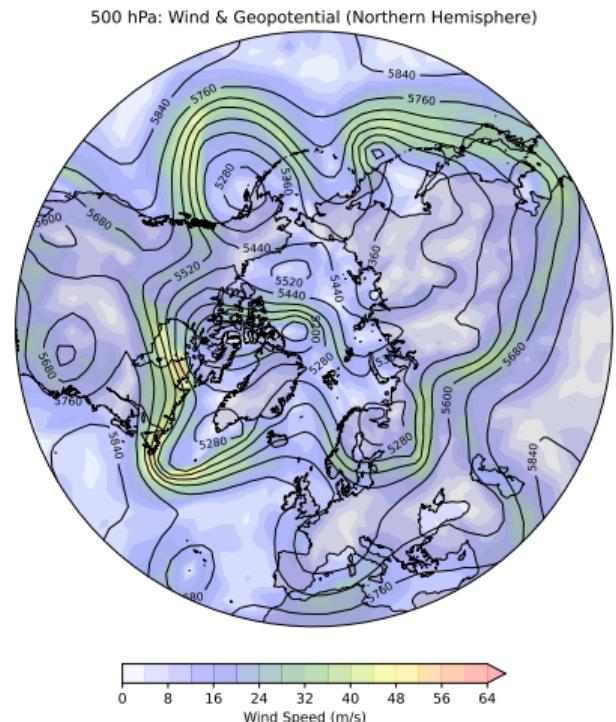
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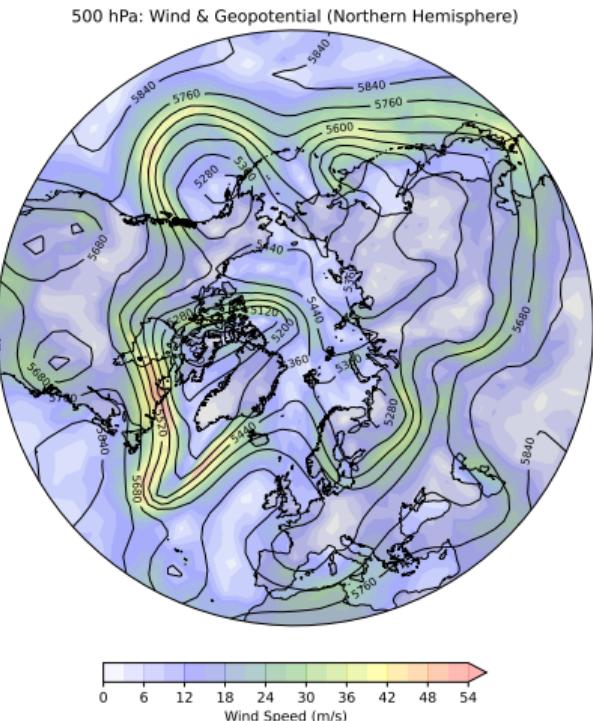
Forecast: 5-May-2025 at 12:00, Level 500hPa



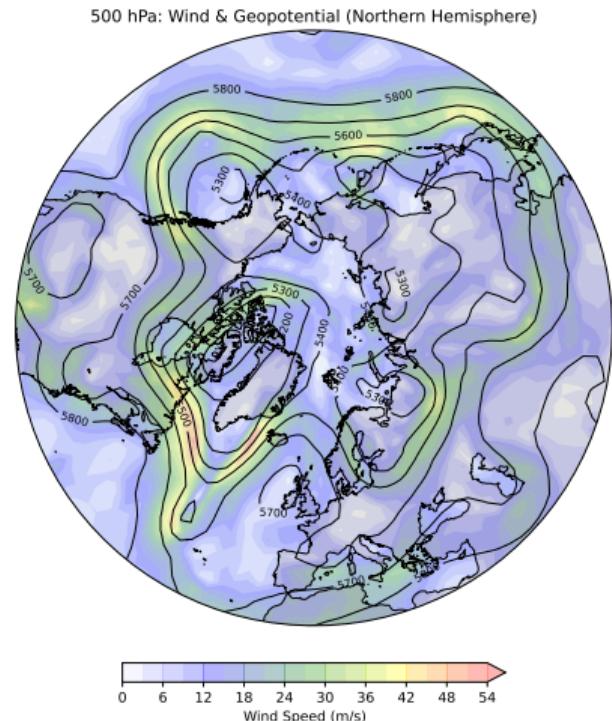
Forecast: 6-May-2025 at 00:00, Level 500hPa



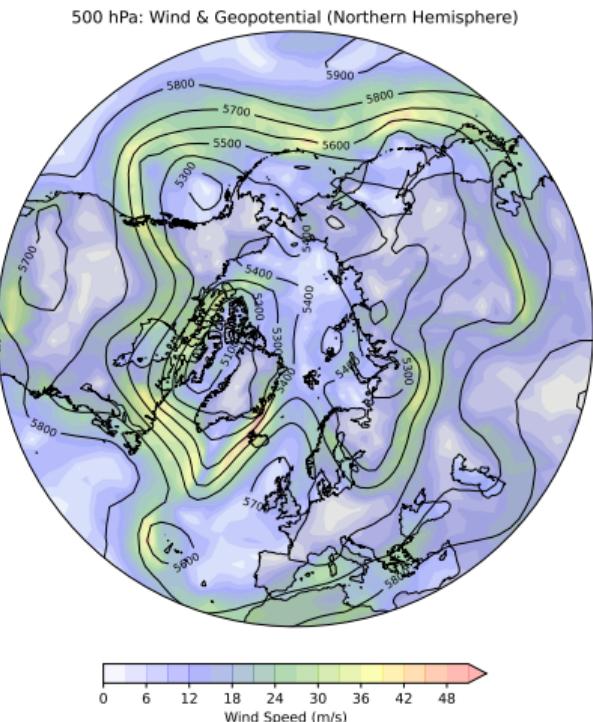
Forecast: 6-May-2025 at 12:00, Level 500hPa



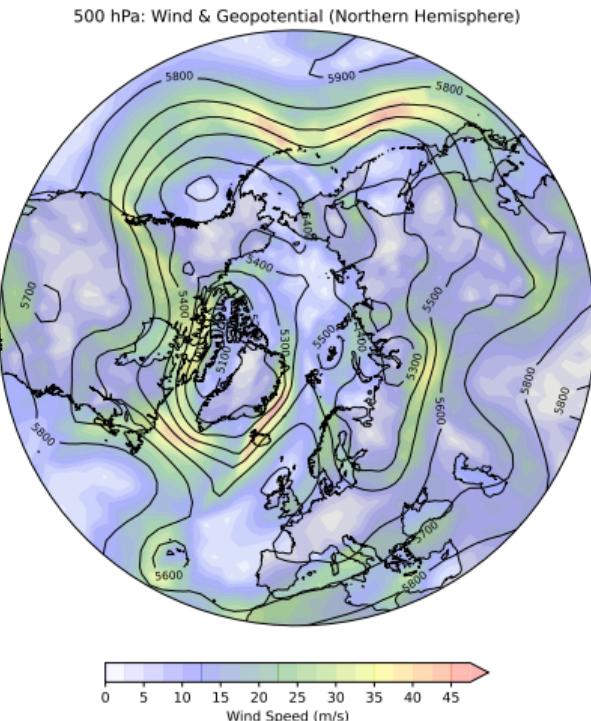
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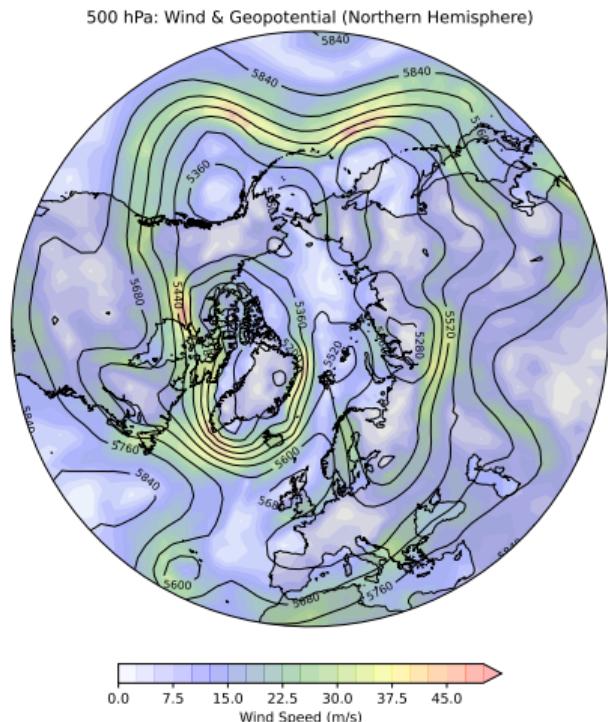
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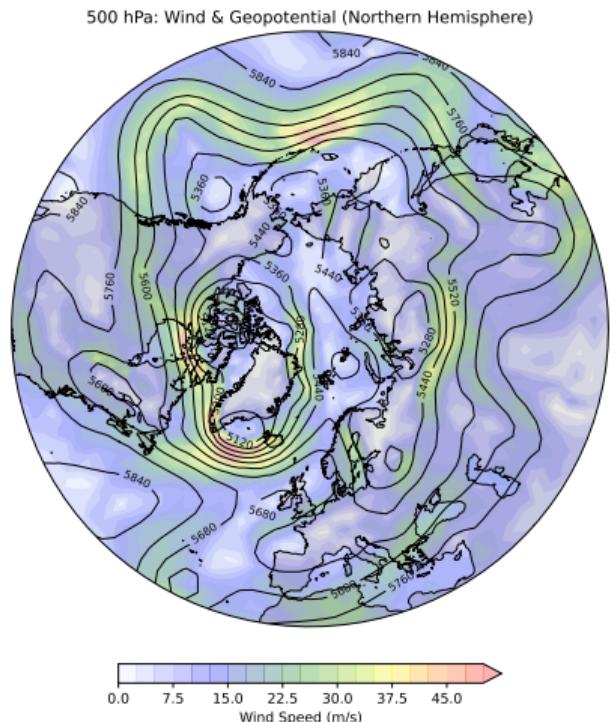
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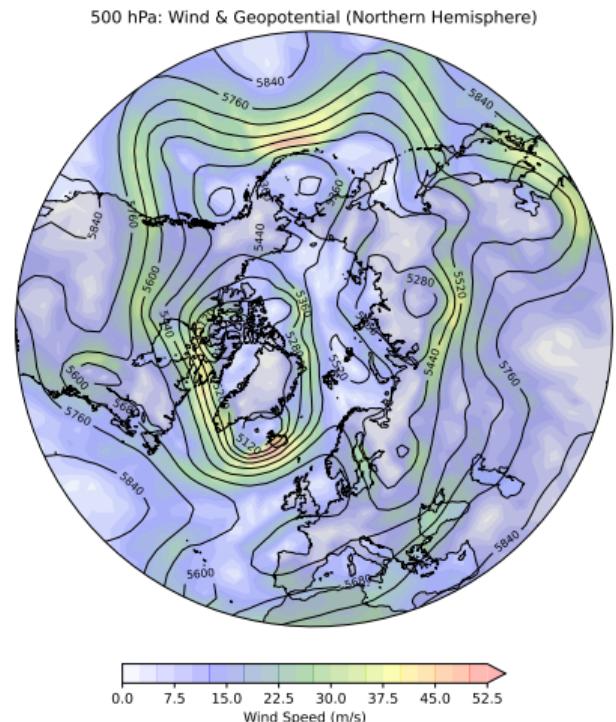
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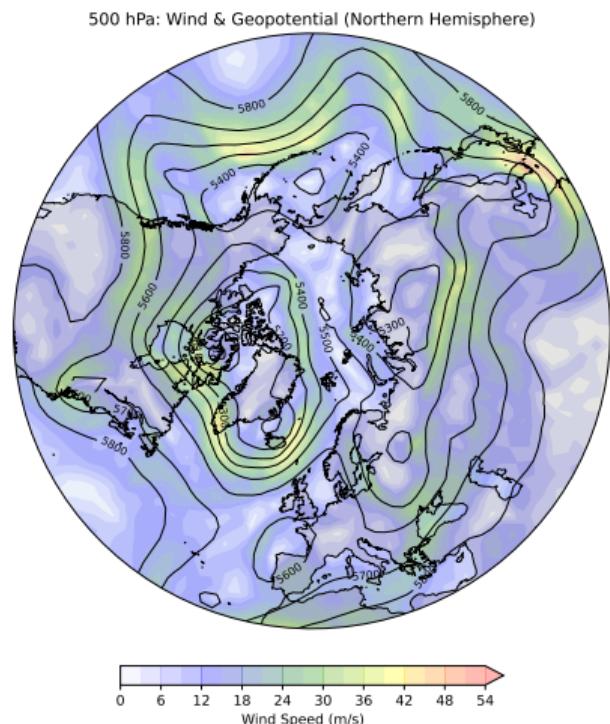
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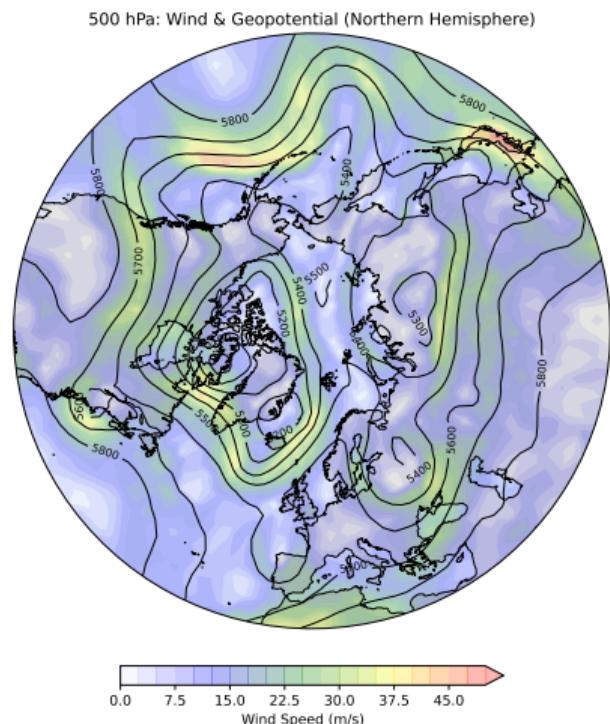
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Forecast: 10-May-2025 at 00:00, Level 500hPa

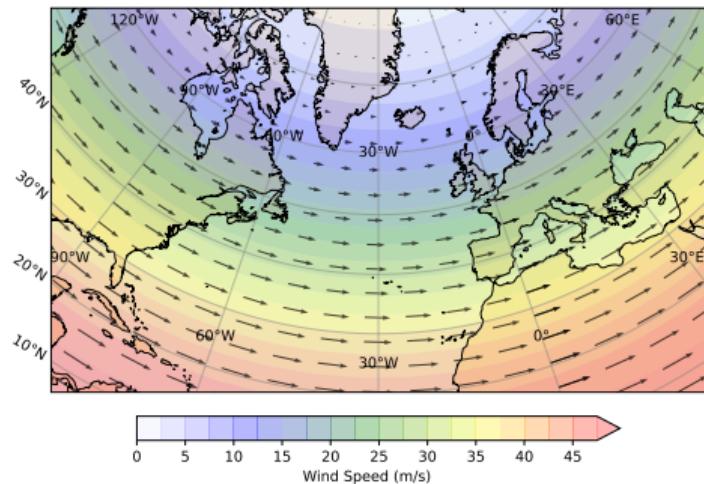


Forecast: 10-May-2025 at 12:00, Level 500hPa



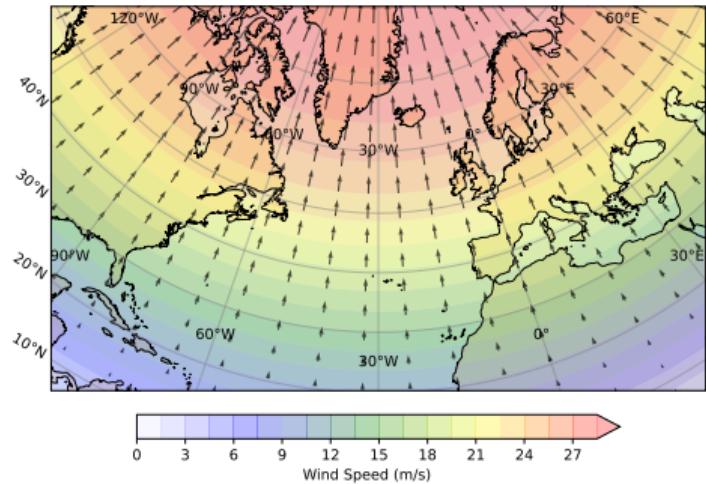
Idealisiertes zonales Windfeld

- Gezeigt ist ein simuliertes **zonales Windfeld**:
 - Reine Ost-West-Strömung ($v = 0$)
 - Geschwindigkeit abhängig von der Breite:
 $u = U_0 \cdot \sin^2(\theta)$
 - Keine Druckgradienten oder vertikale Struktur



Idealisiertes meridionales Windfeld

- Gezeigt ist ein simuliertes **meridionales Windfeld**:
 - Reine Nord-Süd-Strömung ($u = 0$)
 - Geschwindigkeit abhängig von der Breite:
 $v = V_0 \cdot \cos(\theta)$

















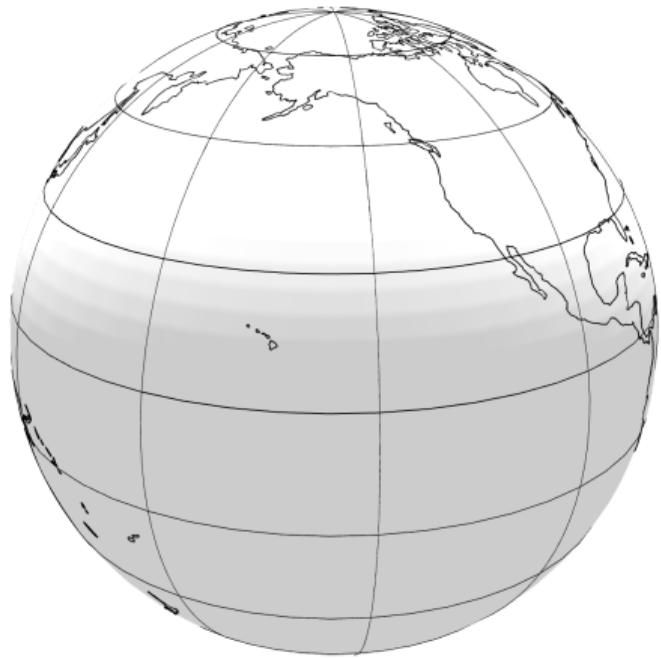


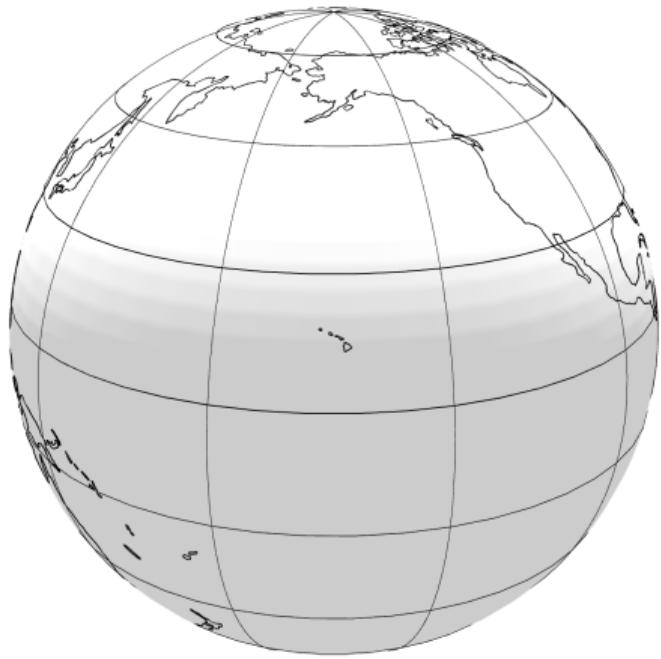


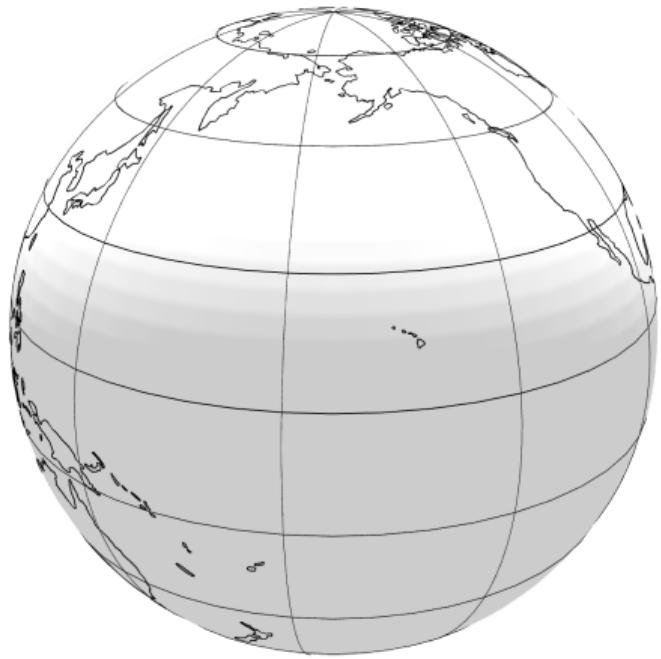


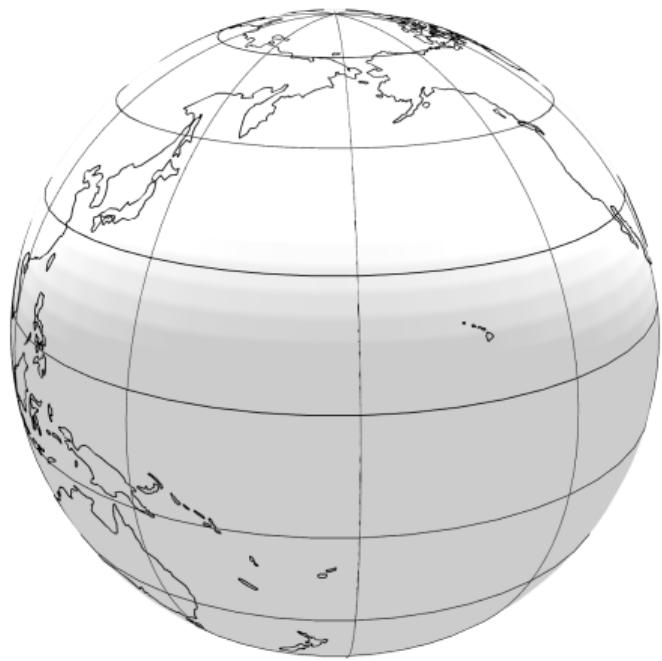




















Corioliskraft: Grundprinzip

- Die **Corioliskraft** ist eine Scheinkraft, die in rotierenden Bezugssystemen wie der Erde wirkt.
- Sie verursacht eine Ablenkung von bewegten Luft- und Wassermassen:
 - **Nordhalbkugel:** Ablenkung nach rechts
 - **Südhalbkugel:** Ablenkung nach links
- Maximale Wirkung an den Polen, null am Äquator.

Mathematische Formulierung

$$\vec{F}_C = -2m(\vec{\Omega} \times \vec{v})$$

- m : Masse des Körpers
- $\vec{\Omega}$: Rotationsvektor der Erde
- \vec{v} : Geschwindigkeit relativ zur Erdoberfläche

Beispiel: Corioliskraft beim Velofahren

Gegeben:

- Geschwindigkeit: $\vec{v} = 8.33 \text{ m/s}$ (30 km/h)
- Masse: $m = 80 \text{ kg}$
- Breite: $\varphi = 47^\circ$ (Zürich)
- Erdrotation:

$$23 \text{ h } 56 \text{ min } 4 \text{ s} \quad \Rightarrow \quad \vec{\Omega} = \frac{2\pi}{86164 \text{ s}} \approx 7.292 \times 10^{-5} \text{ rad/s}$$

Formel:

$$F_C = 2m\vec{v}\vec{\Omega} \sin(\varphi)$$

Einsetzen:

$$F_C \approx 2 \cdot 80 \cdot 8.33 \cdot 7.292 \times 10^{-5} \cdot \sin(47^\circ) \approx 0.070 \text{ N}$$

Breitenabhängigkeit und Coriolis-Parameter

- Der **Coriolis-Parameter** beschreibt die Breitenabhängigkeit:

$$f = 2\Omega \sin(\phi)$$

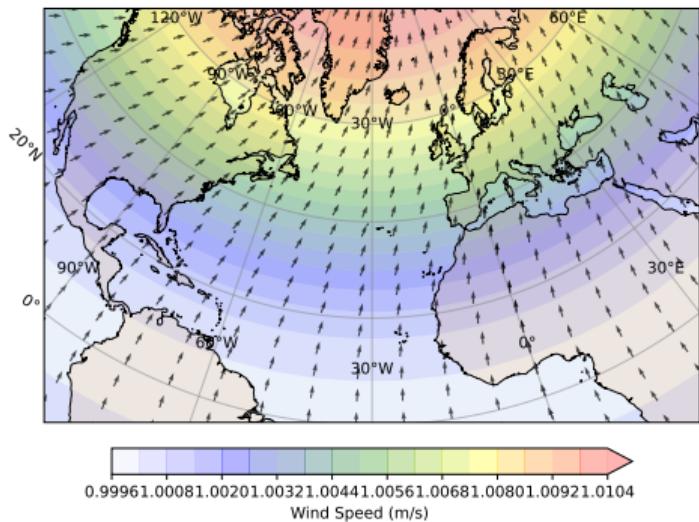
- Seine Änderung mit der Breite ergibt den **β -Parameter**:

$$\beta = \frac{\partial f}{\partial y} = \frac{2\Omega \cos(\phi)}{a}$$

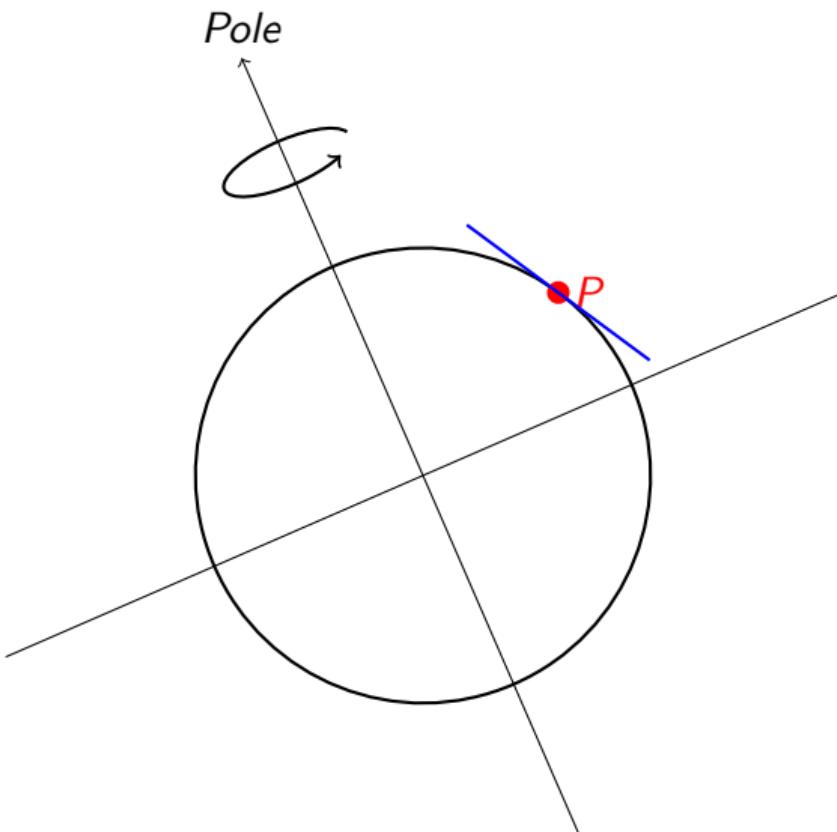
- a : Erdradius, y : Nord-Süd-Koordinate

Simulation der Corioliskraft auf Nordströmung

- Darstellung: Ablenkung von Luftpaketen bei rein meridionaler Startgeschwindigkeit ($v = 1, u = 0$)
- Nach `steps = 100` Zeitschritten:
 - Auf Nordhalbkugel: Ablenkung nach Osten
 - Auf Südhalbkugel: Ablenkung nach Westen
- Breitenabhängigkeit durch $f = 2\Omega \sin(\phi)$



β -Ebene Approximation



Was ist die β -Ebene?

- Die **β -Ebene** ist eine lokale Approximation der Erdkugel nahe einer bestimmten Breite ϕ_0 .
- Ziel: Vereinfachung der Corioliskraft für mathematische Modelle.
- Der Coriolisparameter f wird linearisiert:

$$f(y) = f_0 + \beta y$$

mit:

- $f_0 = 2\Omega \sin(\phi_0)$: Coriolisparameter an der Referenzbreite
- $\beta = \left. \frac{\partial f}{\partial y} \right|_{\phi_0} = \frac{2\Omega \cos(\phi_0)}{a}$
- y : meridionale Entfernung vom Referenzbreitenkreis

Was ist Vortizität?

- **Vortizität** beschreibt die lokale Rotation in einer Strömung.
- Definiert als das **Rotationsfeld** des Geschwindigkeitsfeldes:

$$\vec{\zeta} = \nabla \times \vec{u}$$

- Für eine zweidimensionale Strömung $\vec{u} = (u(x, y), v(x, y))$ ist nur die z-Komponente relevant:

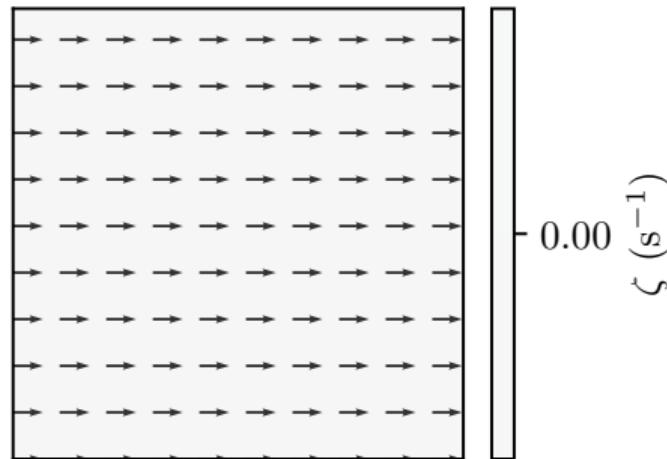
$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

- $\zeta > 0$: Zyklonale Rotation (gegen den Uhrzeigersinn)
- $\zeta < 0$: Antizyklonale Rotation (im Uhrzeigersinn)

Zero Vorticity (Uniform Flow)

- $\vec{u} = (2, 0)$
- Uniform horizontal flow
- No shear or curvature
- $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = 0 - 0 = 0$

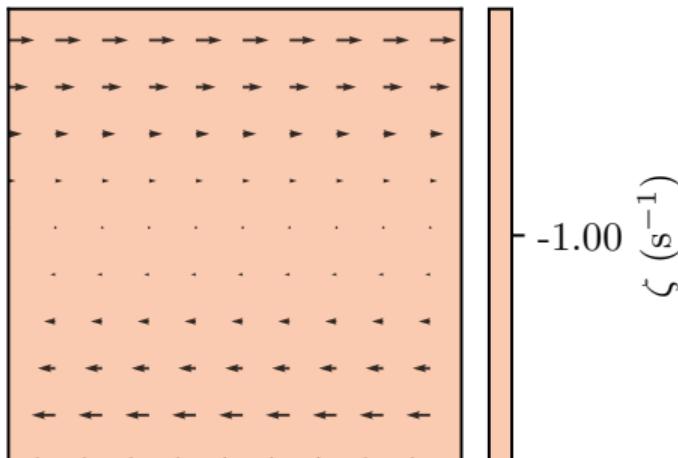
Zero Vorticity (Uniform Flow)



Shear Vorticity

- $\vec{u} = (y, 0)$
- Horizontal shear: $\frac{\partial u}{\partial y} = 1$
- $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = 0 - 1 = -1$

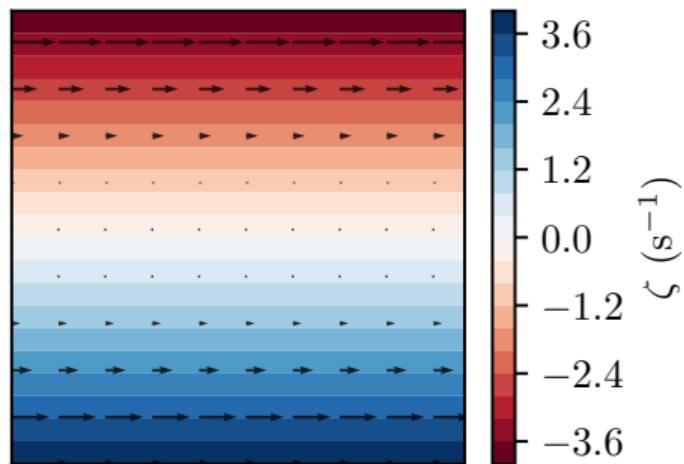
Shear Vorticity



Nonlinear Shear Vorticity

- $\vec{u} = (y^2, 0)$
- Antisymmetric vorticity field
- Stronger at larger $|y|$
- $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = 0 - 2y = -2y$

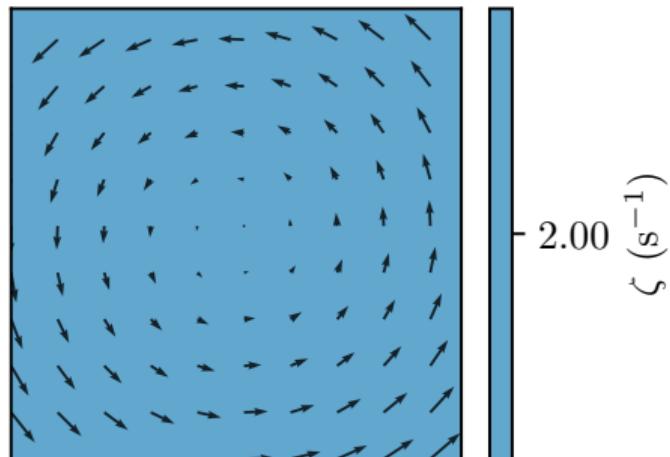
Nonlinear Shear Vorticity



Positive Vorticity (Cyclonic)

- $\vec{u} = (-y, x)$
- Pure rotation, counter-clockwise
- $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = 1 - (-1) = 2$

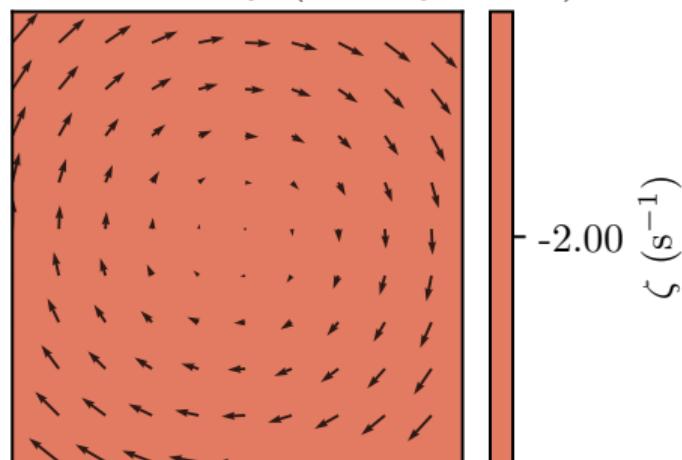
Positive Vorticity (Cyclonic)



Negative Vorticity (Anticyclonic)

- $\vec{u} = (y, -x)$
- Clockwise rotation
- $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = -1 - 1 = -2$

Negative Vorticity (Anticyclonic)



Absolute Vortizität

- In einem rotierenden Bezugssystem (wie der Erde) ergibt sich die **absolute Vortizität** zu:

$$\eta = f + \zeta$$

- ζ : relative Vortizität (durch Scherung und Krümmung der Strömung)
- $f = 2\Omega \sin \phi$: Coriolis-Parameter, abhängig von der geografischen Breite

Konservierung der potentiellen Vortizität

- Die **potenzielle Vortizität (PV)** ist definiert als:

$$q = \frac{\eta}{H} = \frac{f + \zeta}{H}$$

- η : absolute Vortizität, bestehend aus $f + \zeta$
- H : effektive Schichtdicke (z. B. Troposphärenhöhe oder isentrope Dicke)
- In einer reibungsfreien, adiabatischen Atmosphäre gilt:

$$\frac{Dq}{Dt} = 0$$

Warum ist PV-Erhaltung wichtig für Rossby-Wellen?

- Rossby-Wellen entstehen durch meridionale Bewegung von Luftpaketen (nach Norden oder Süden)
- Dabei ändert sich der Coriolis-Parameter: $f = 2\Omega \sin \phi$
- **PV-Erhaltung:**

$$q = \frac{f + \zeta}{H} = \text{konstant}$$

- Wenn ein Luftpaket nach Norden wandert: $f \uparrow \Rightarrow \zeta \downarrow$
- Folge: Luftpaket rotiert weniger → Rückstellkraft → beginnt zu oszillieren
- **Diese Oszillation ist die Rossby-Welle**
- Ohne PV-Erhaltung gäbe es keine Rückstellmechanismus → keine Welle

Rossby-Wellen

- In Äquatornähe dominiert eine mittlere Ost-West-Strömung U
- Wir betrachten kleine Abweichungen davon:

$$u' = U + u, \quad v' = v \quad \text{mit } u, v \ll U$$

- Die Strömung ist quellenfrei \rightarrow Stromfunktion ψ existiert:

$$u = -\frac{\partial \psi}{\partial y}, \quad v = \frac{\partial \psi}{\partial x}$$

Zirkulation und Drehimpuls

- Relative Vorticity (Zirkulation):

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = \Delta\psi$$

- Absolute Vorticity:

$$\zeta + f \quad (\text{mit Coriolisparameter } f = f(y))$$

- Annahme: Erhaltung der absoluten Vorticity:

$$\frac{d}{dt}(\zeta + f) = 0$$

Bewegungsgleichung - Herleitung

- Kettenregel für totale Ableitung:

$$\frac{d}{dt}(\zeta + f) = \frac{\partial \zeta}{\partial t} + (U + u)\frac{\partial \zeta}{\partial x} + v \left(\frac{\partial \zeta}{\partial y} + \frac{\partial f}{\partial y} \right)$$

- Näherungen:

- $u \ll U \rightarrow$ vernachlässigbar
- $\partial \zeta / \partial y \ll \partial f / \partial y$
- $\partial f / \partial y = \beta$
- $v = \frac{\partial \psi}{\partial x}$

- Daraus ergibt sich:

$$\frac{\partial \zeta}{\partial t} + U \frac{\partial \zeta}{\partial x} + \beta \frac{\partial \psi}{\partial x} = 0$$

- Mit $\zeta = \Delta \psi$:

$$\frac{\partial \Delta \psi}{\partial t} + U \frac{\partial \Delta \psi}{\partial x} + \beta \frac{\partial \psi}{\partial x} = 0$$

Wellenlösung der Gleichung

- Ansatz: ebene Wellen

$$\psi(x, y, t) = \cos(kx + ly - \omega t)$$

- Einsetzen in Gleichung ergibt Dispersionsrelation:

$$\omega = U k - \frac{\beta k}{k^2 + l^2}$$

- Phasengeschwindigkeit:

$$c = \frac{\omega}{k} = U - \frac{\beta}{k^2 + l^2}$$

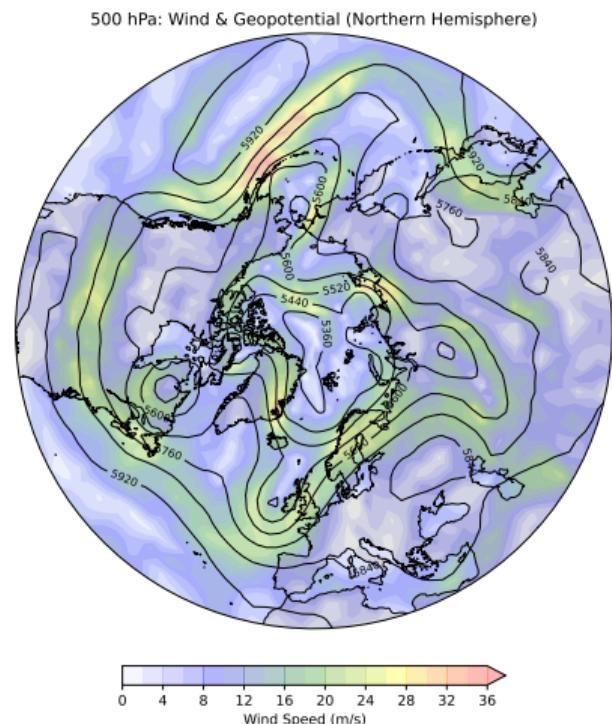
- Interpretation: westwärts laufende Wellen mit geringer Geschwindigkeit als U

Extremereignisse 2010: Russland und Pakistan

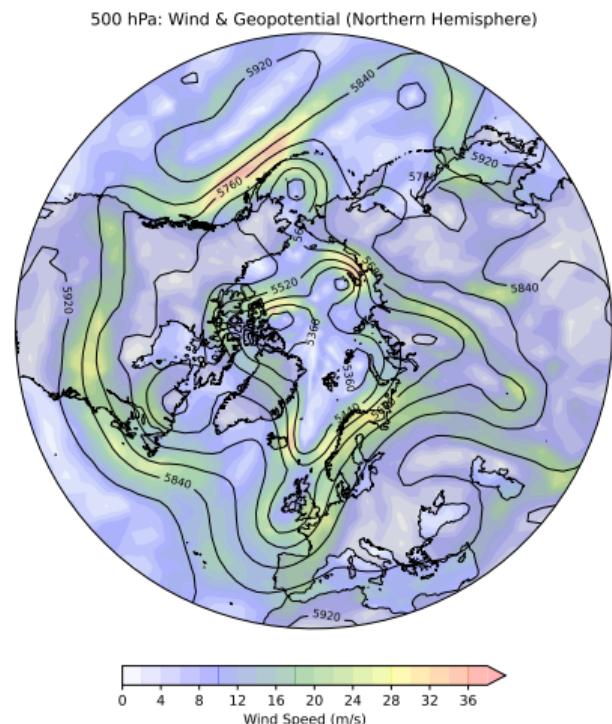
- Sommer 2010: Zwei extreme Wetterereignisse gleichzeitig
 - **Russland:** Hitzewelle, >40 °C, Waldbrände, Smog, tausende Todesfälle
 - **Pakistan:** Jahrhundertflut, Monsunregen, 20 Mio. Menschen betroffen
- Ursache: **Quasi-stationäre Rossby-Welle mit $k = 7$**
 - Hoch über Russland → blockierte Hitze
 - Tief über Pakistan → anhaltender Monsunregen
- Atmosphärische Wellenstruktur führte zu **gleichzeitigen Extremen**
- Beispiel für Wirkung grosskaliger Dynamik auf regionale Wetterkatastrophen ¹

¹Petoukhov et al. (2013), PNAS, DOI: [10.1073/pnas.1222000110](https://doi.org/10.1073/pnas.1222000110)

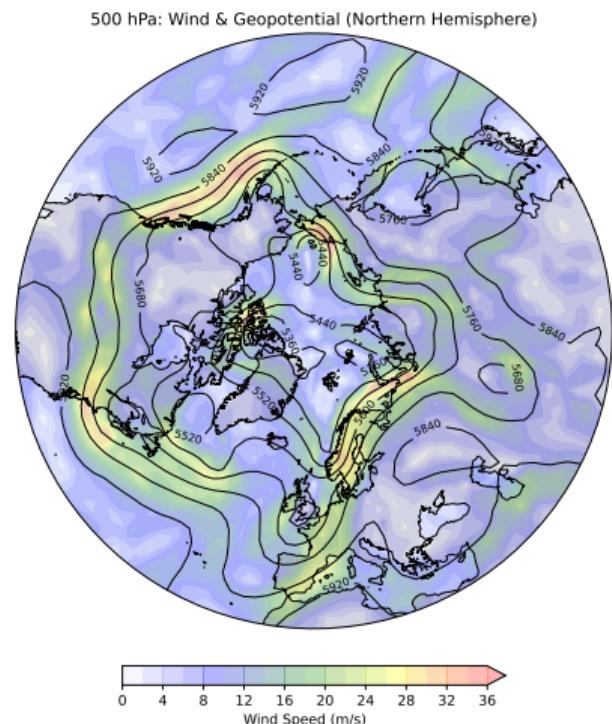
Forecast: 20-July-2010 at 12:00, Level 500hPa



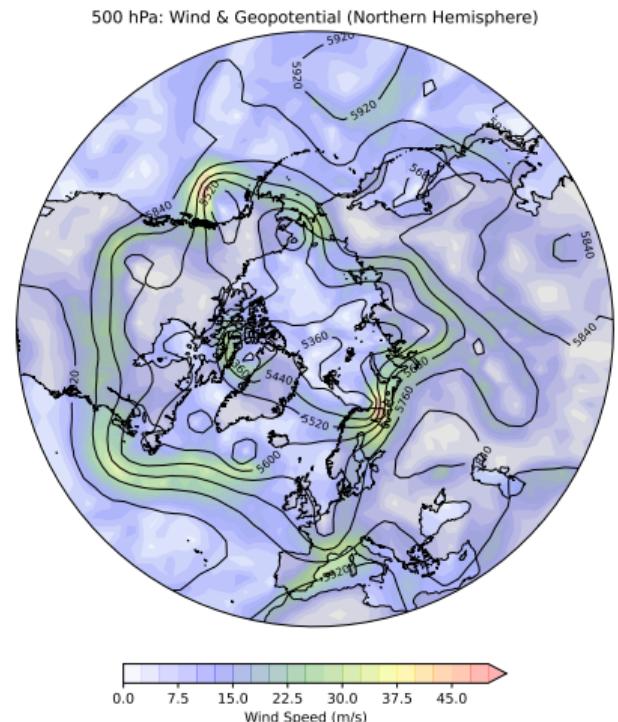
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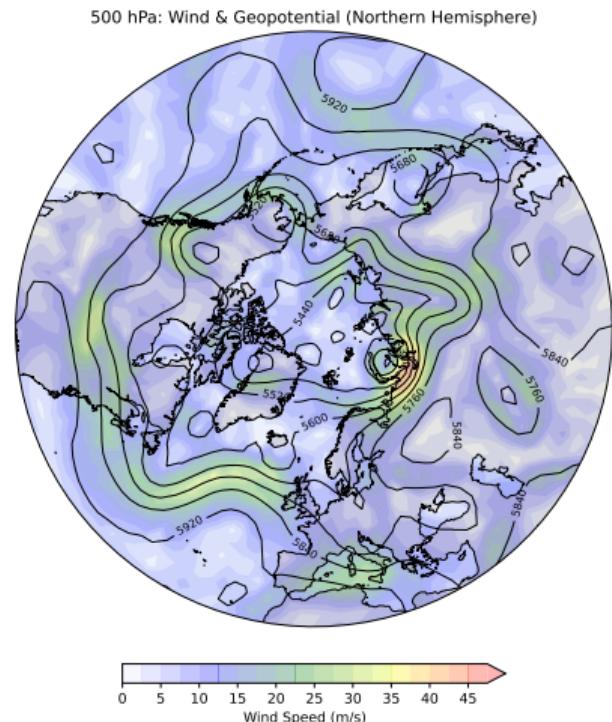
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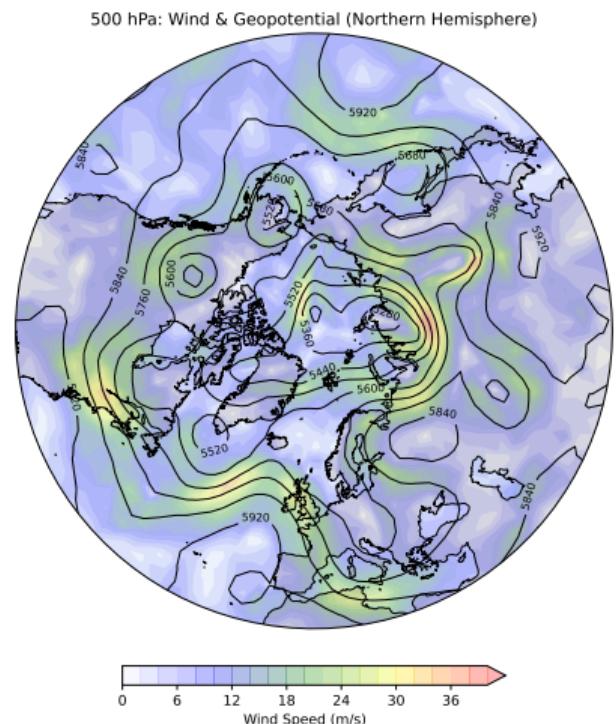
Forecast: 23-July-2010 at 12:00, Level 500hPa



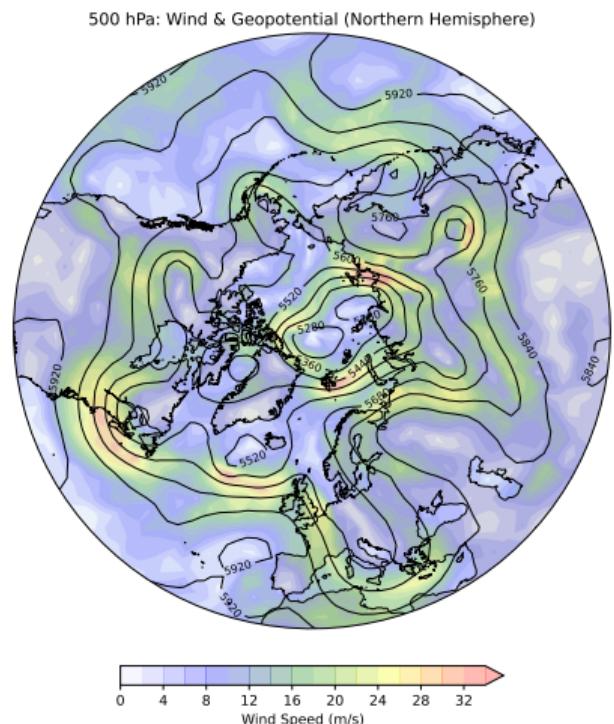
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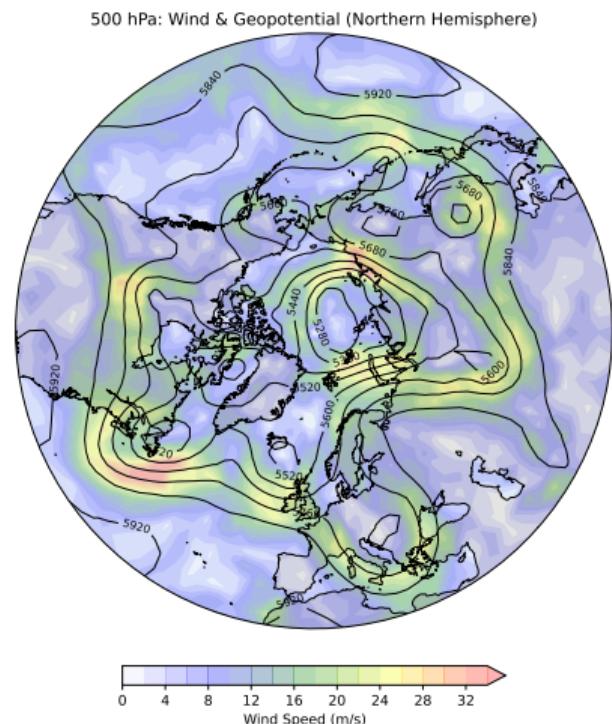
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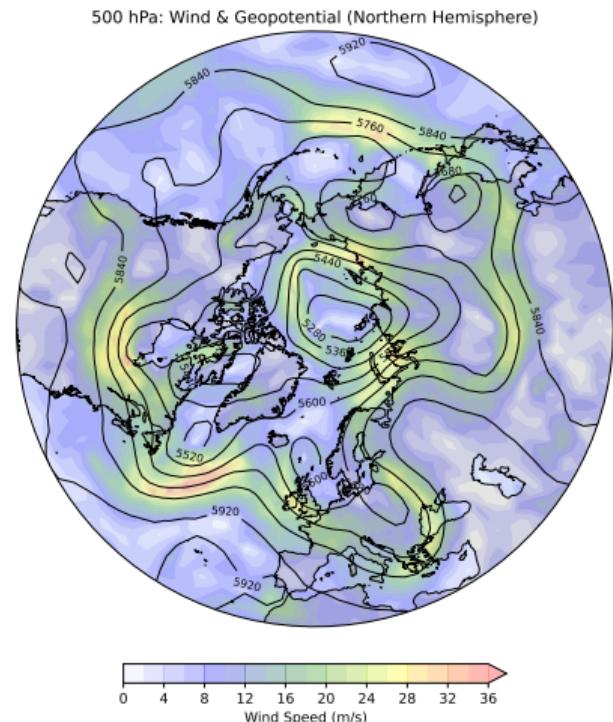
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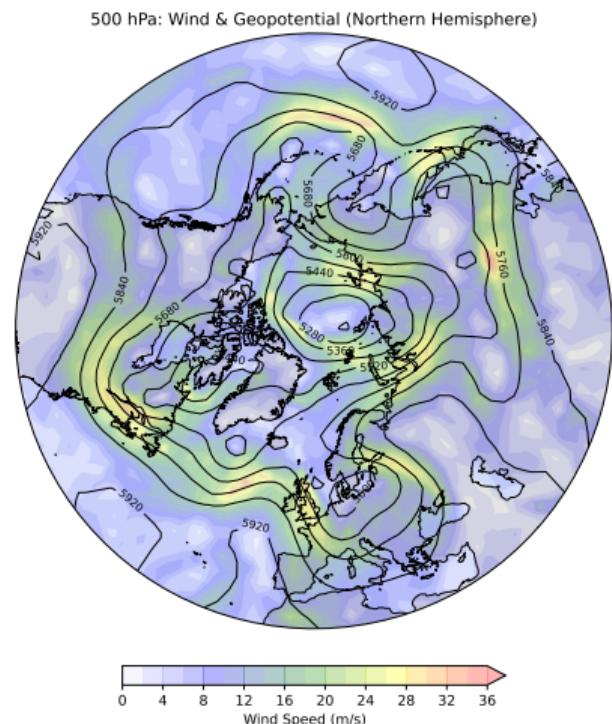
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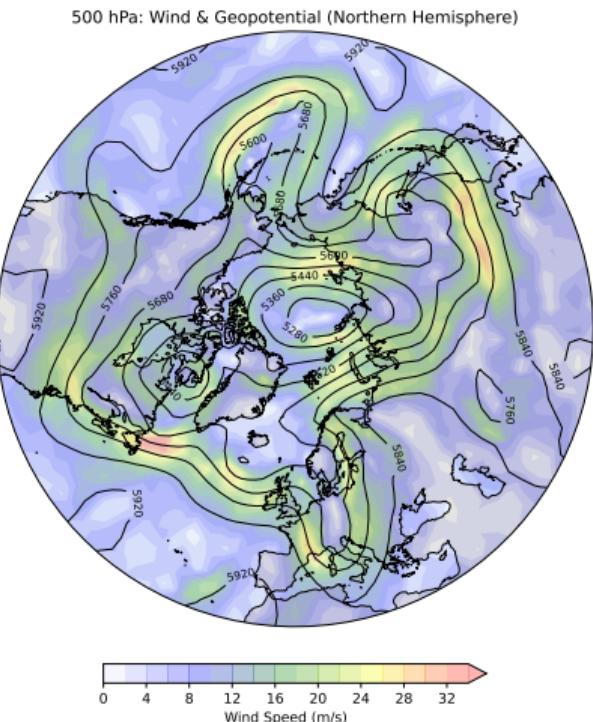
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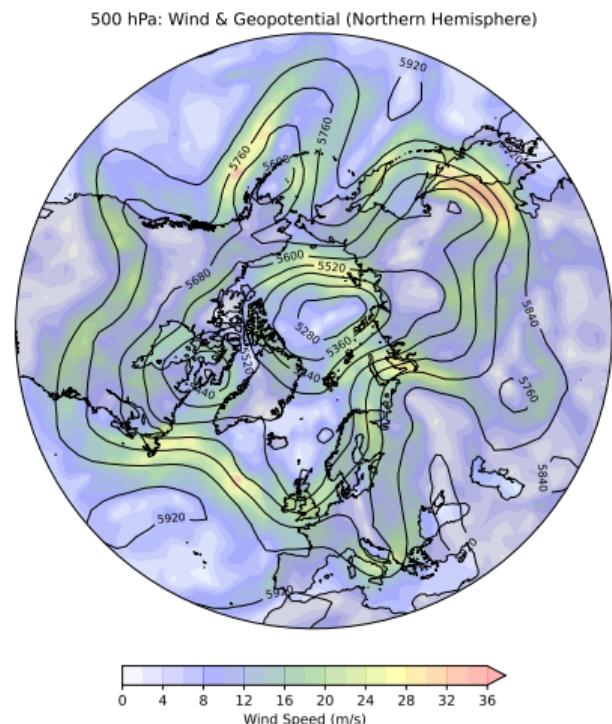
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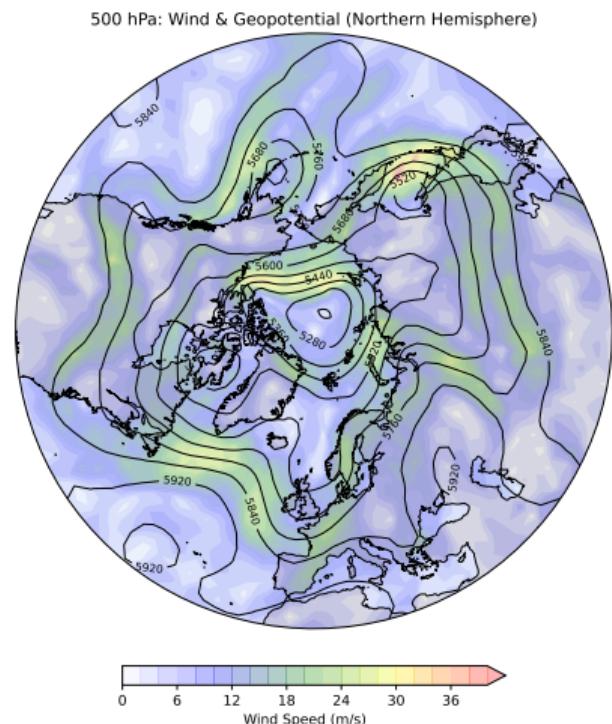
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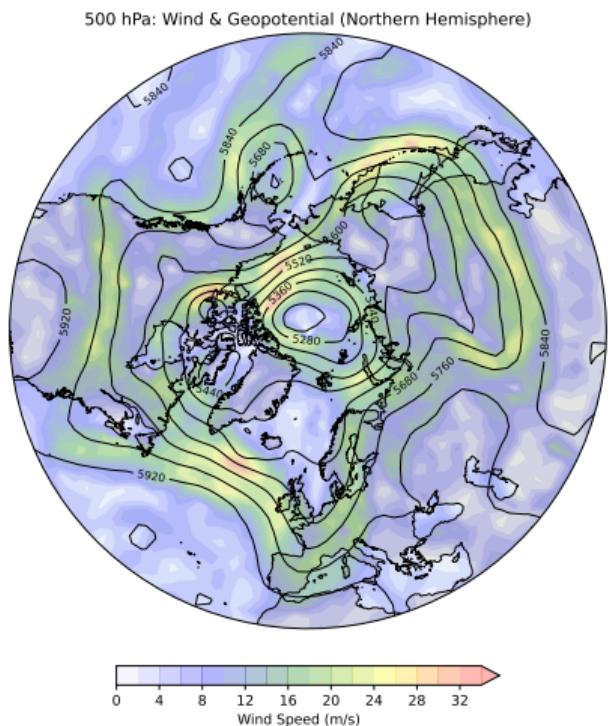
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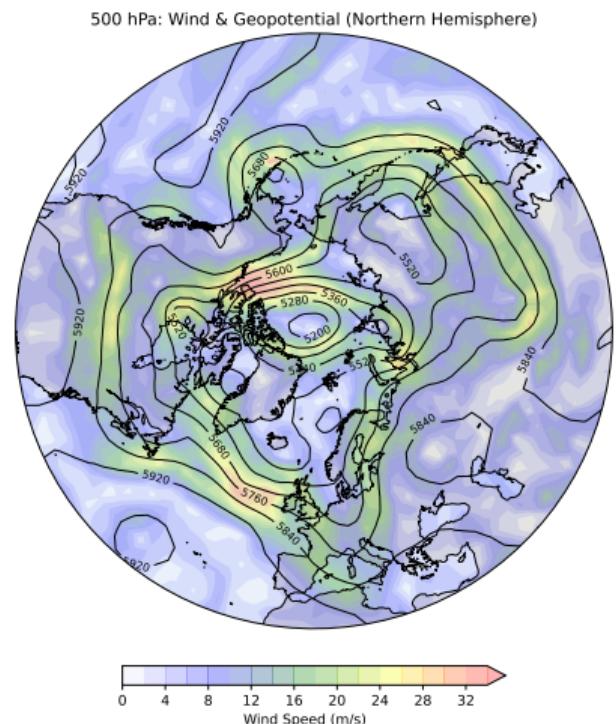
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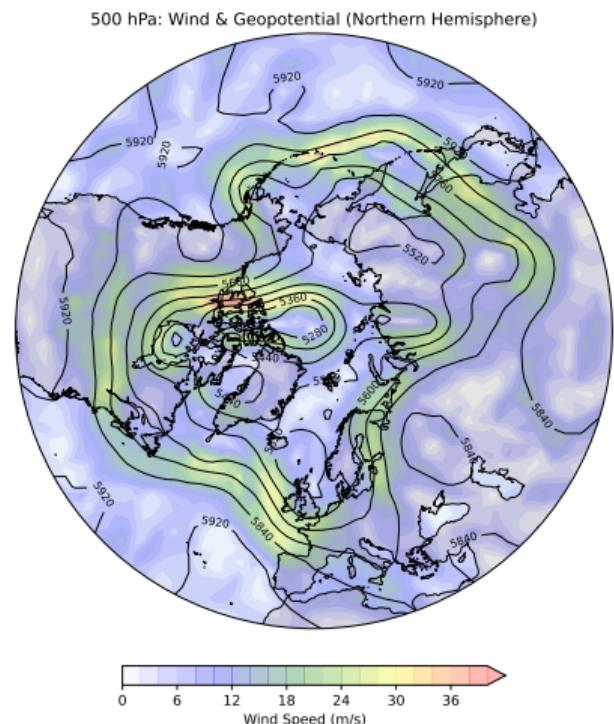
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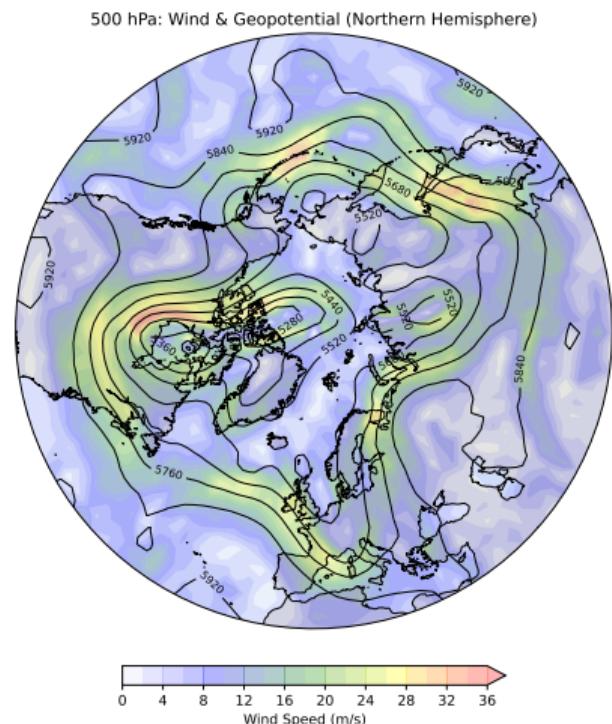
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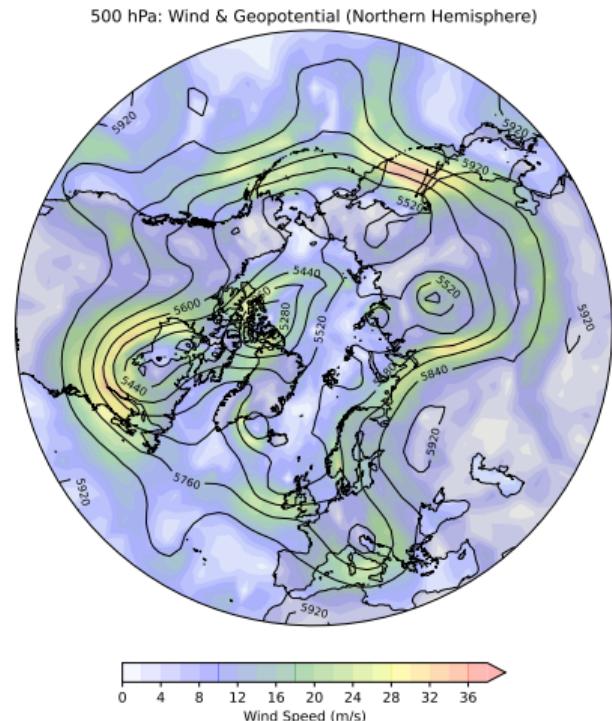
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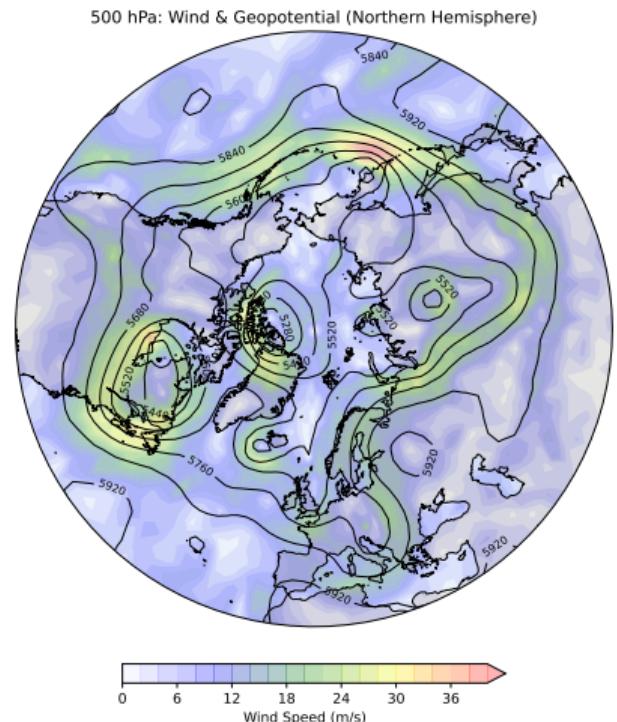
Forecast: 5-August-2010 at 12:00, Level 500hPa



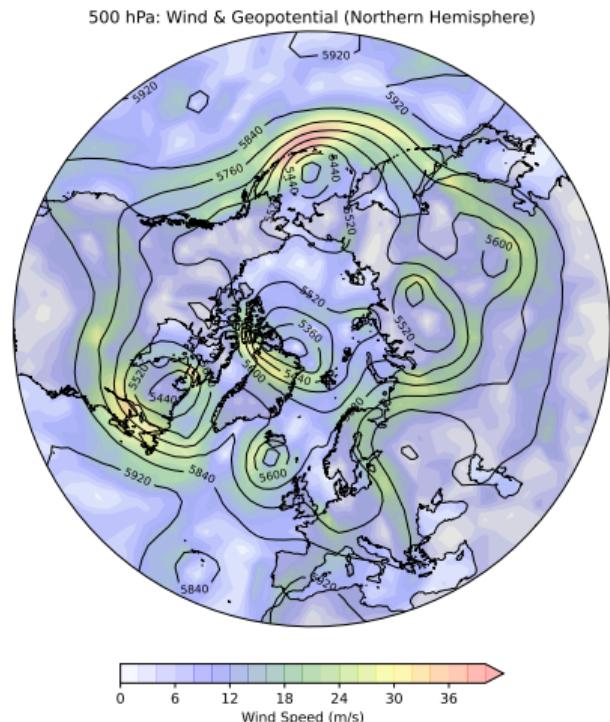
Forecast: 6-August-2010 at 12:00, Level 500hPa



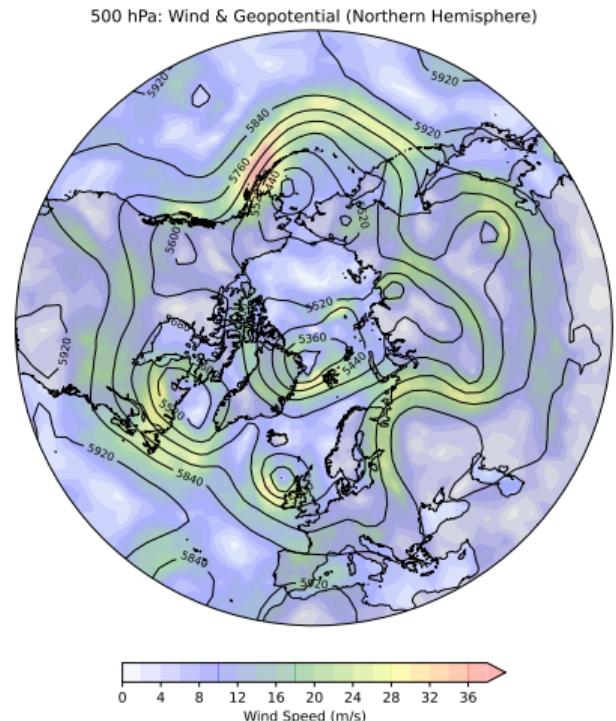
Forecast: 7-August-2010 at 12:00, Level 500hPa



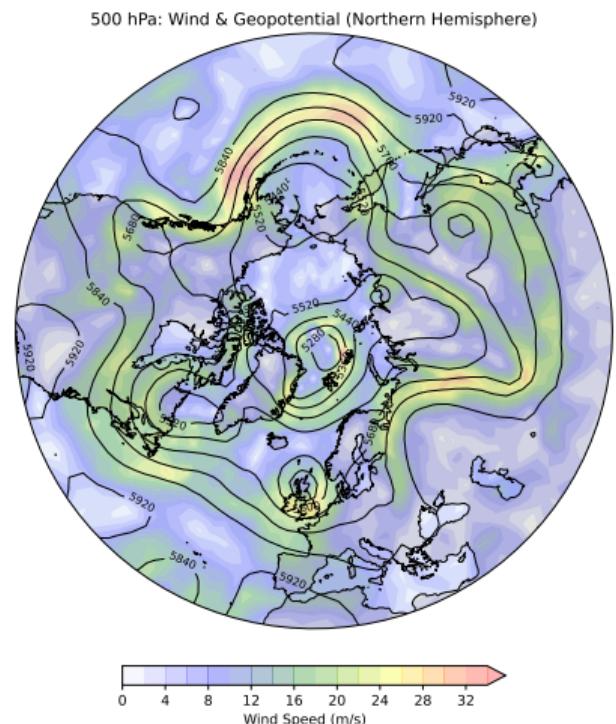
Forecast: 8-August-2010 at 12:00, Level 500hPa



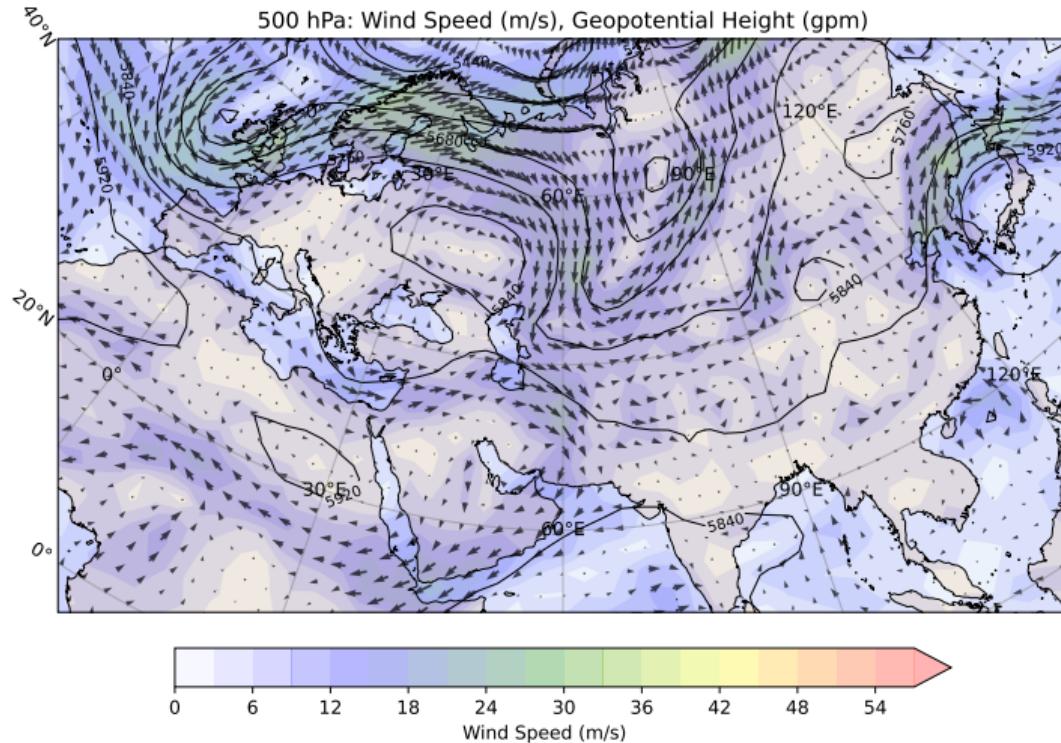
Forecast: 9-August-2010 at 12:00, Level 500hPa



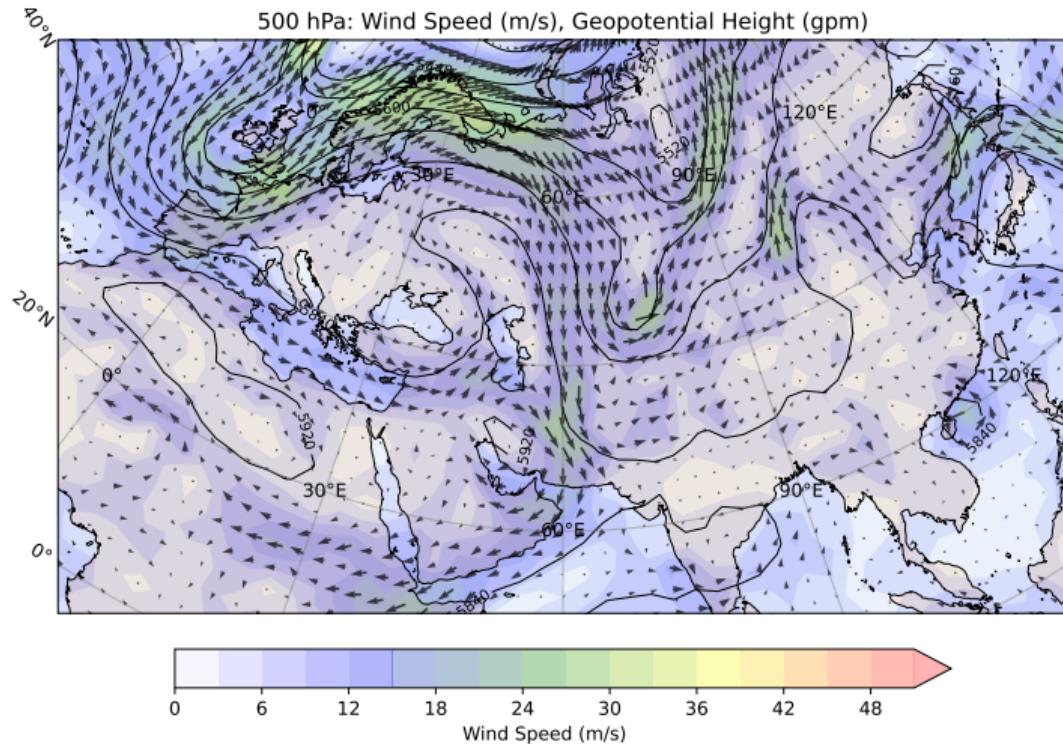
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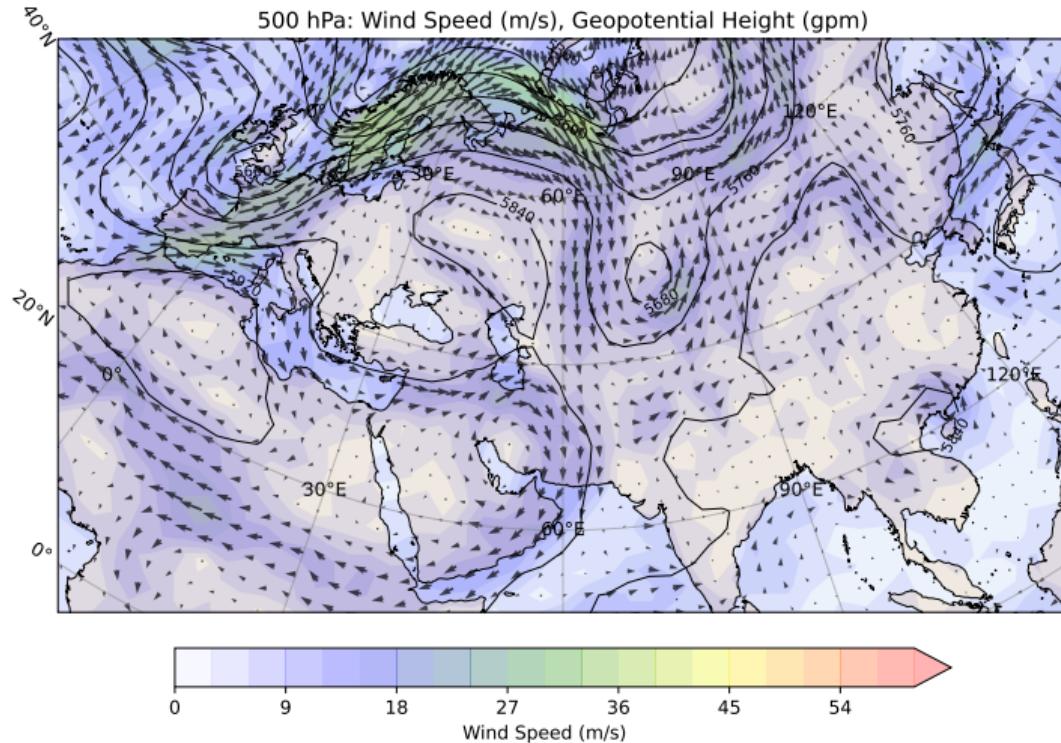
Forecast: 20-July-2010 at 12:00, Level 500hPa



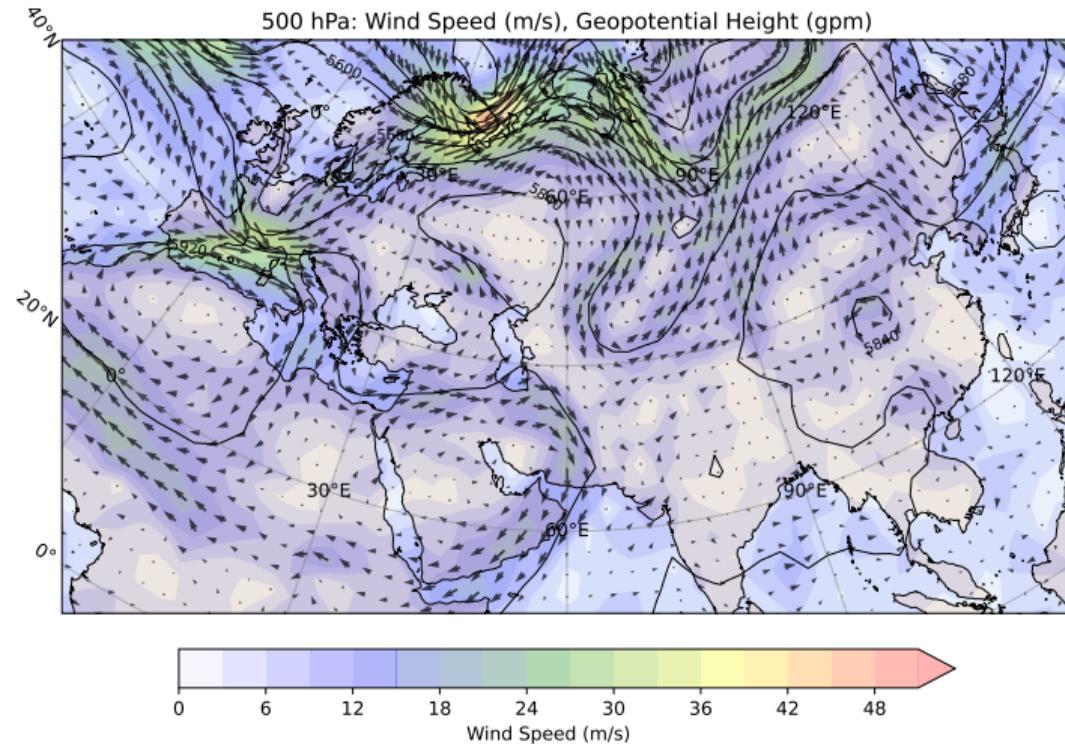
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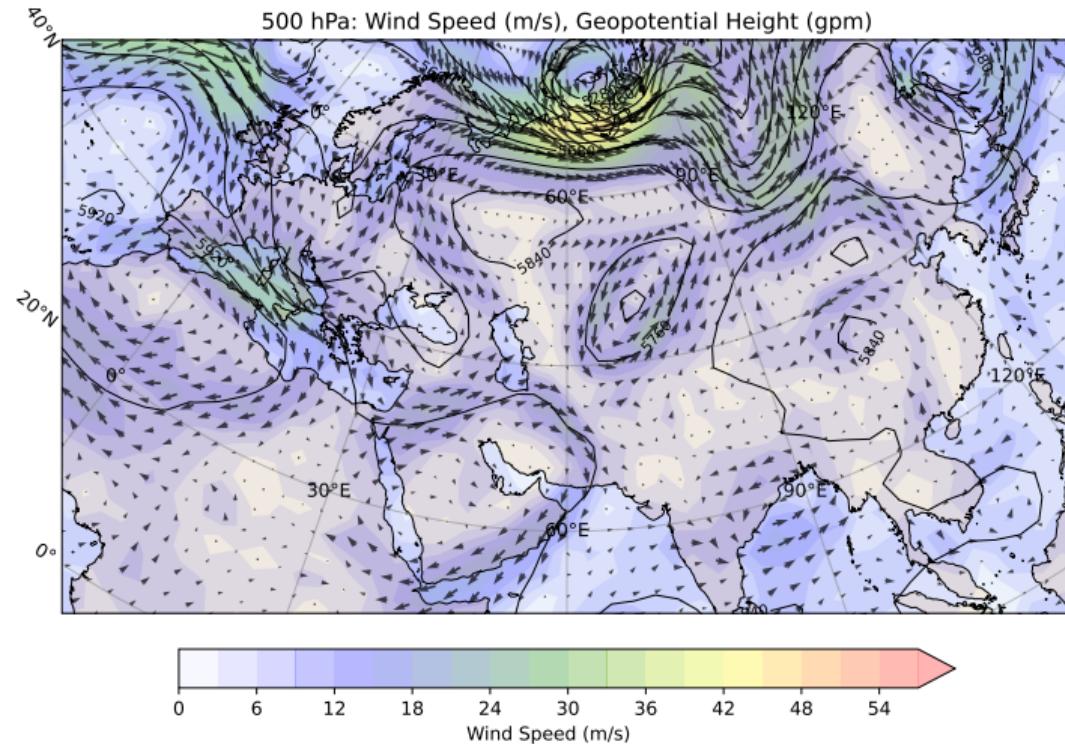
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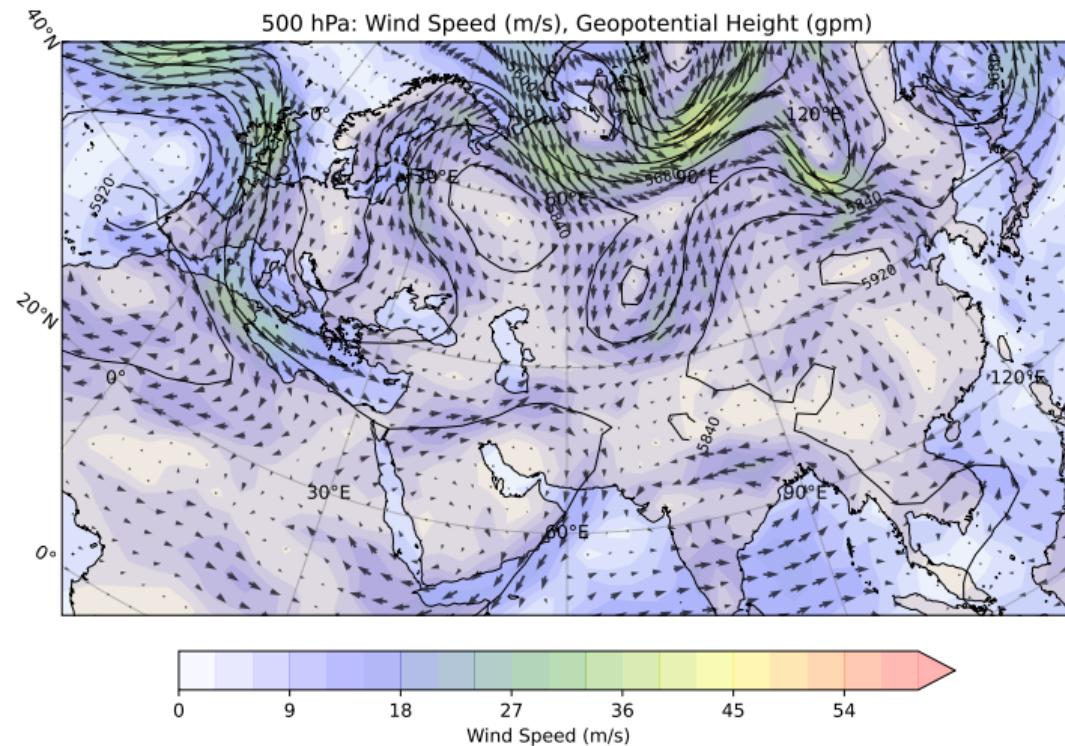
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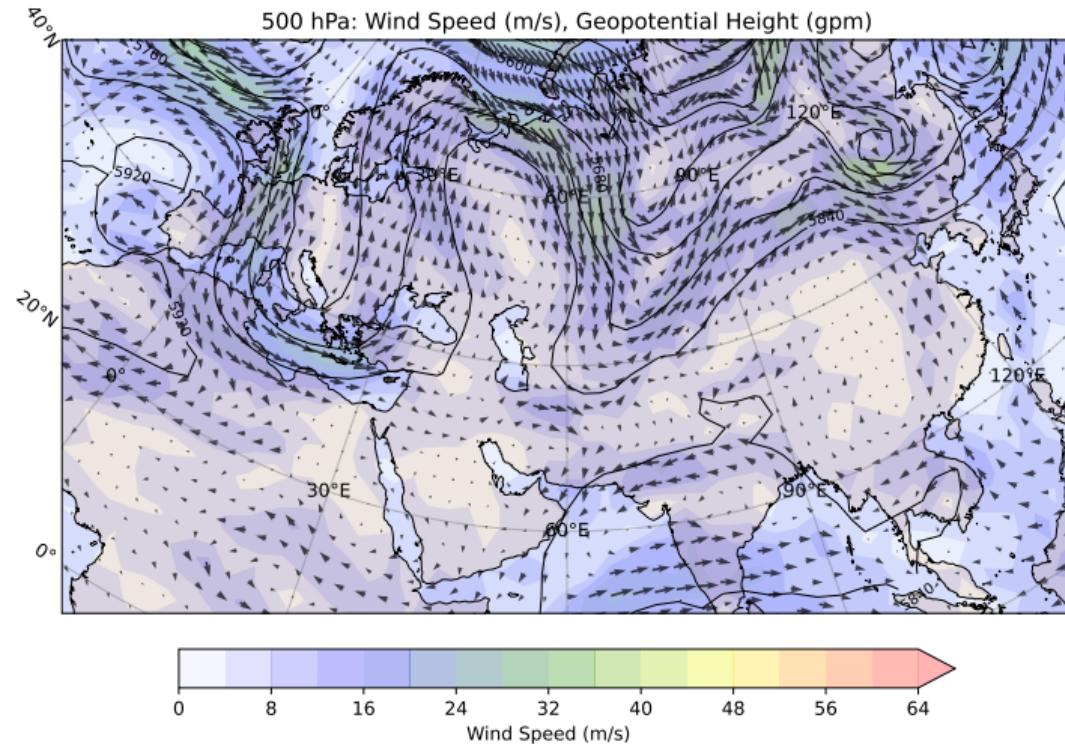
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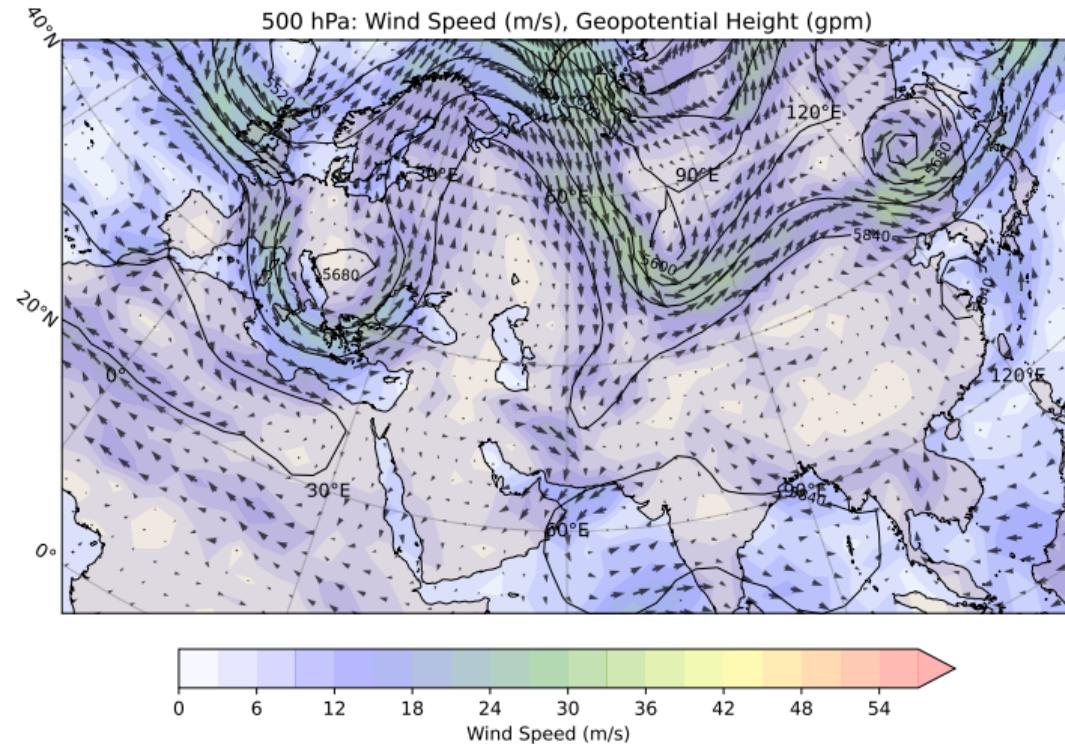
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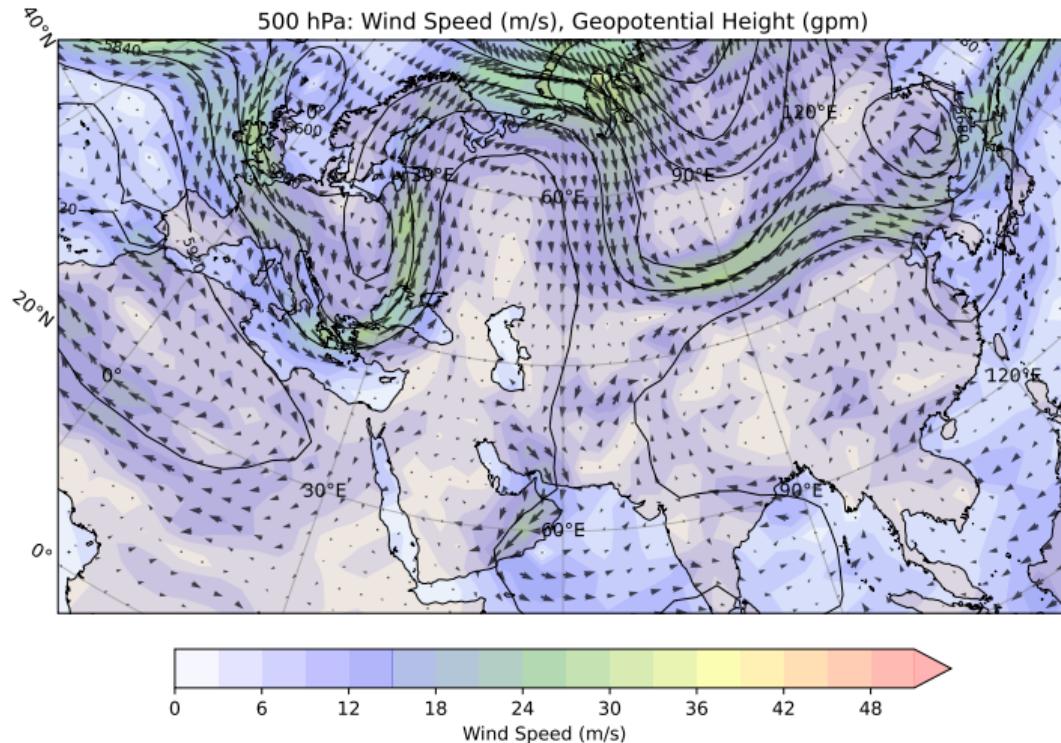
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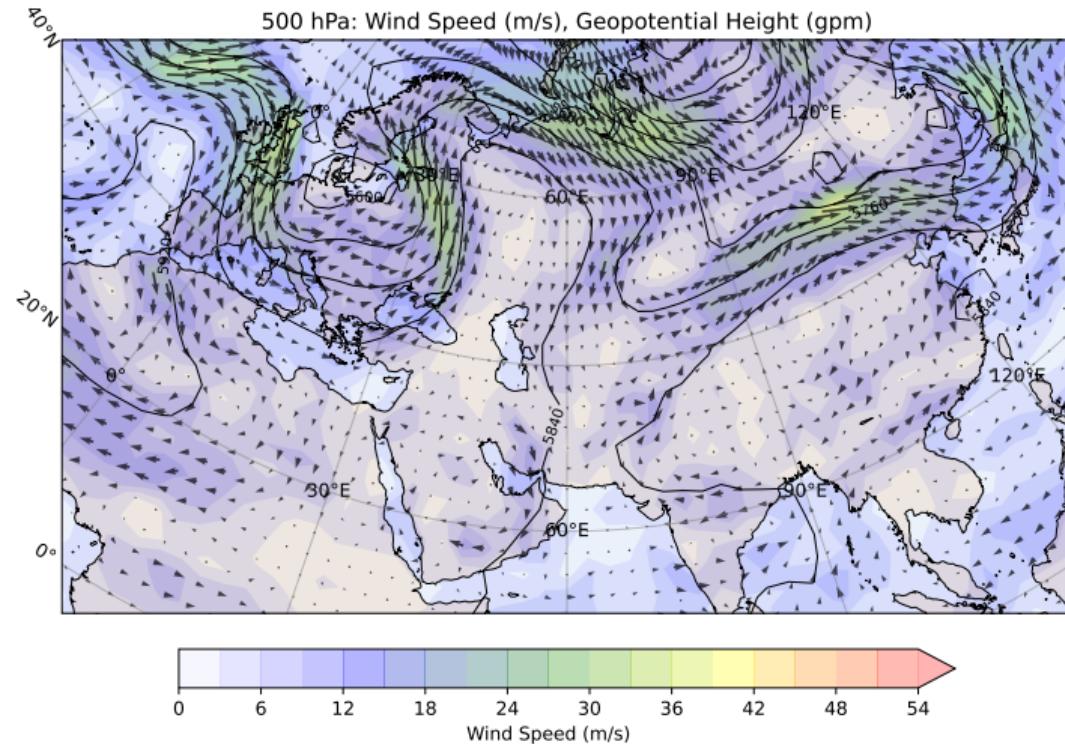
Forecast: 27-July-2010 at 12:00, Level 500hPa



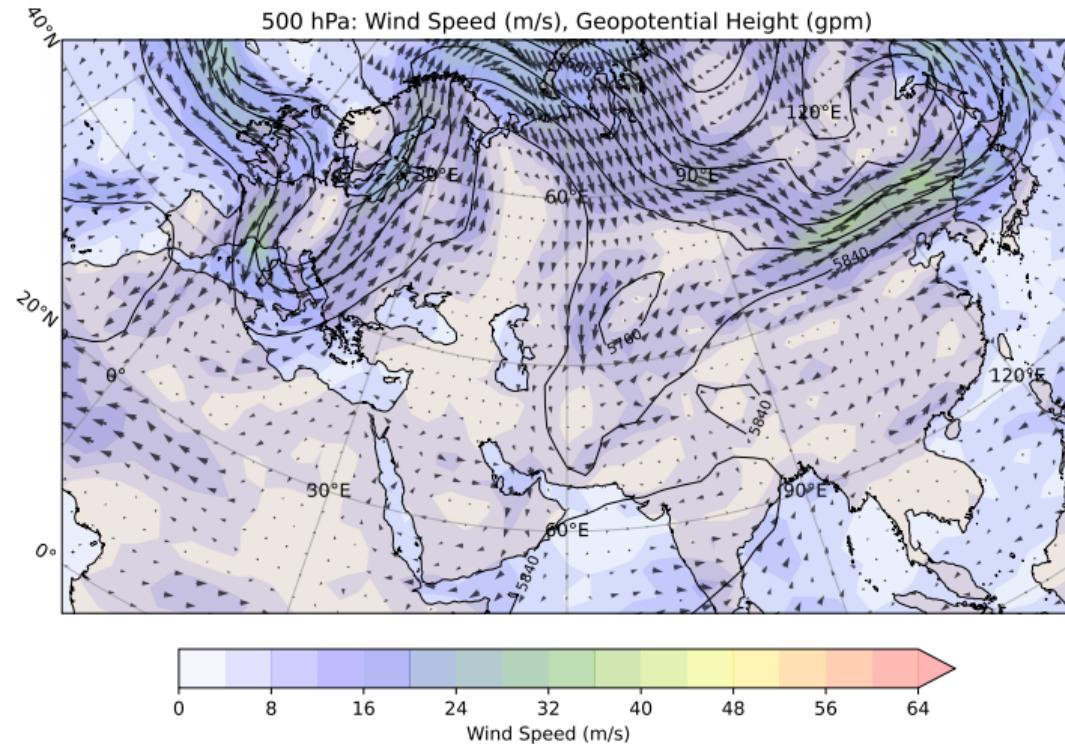
Forecast: 28-July-2010 at 12:00, Level 500hPa



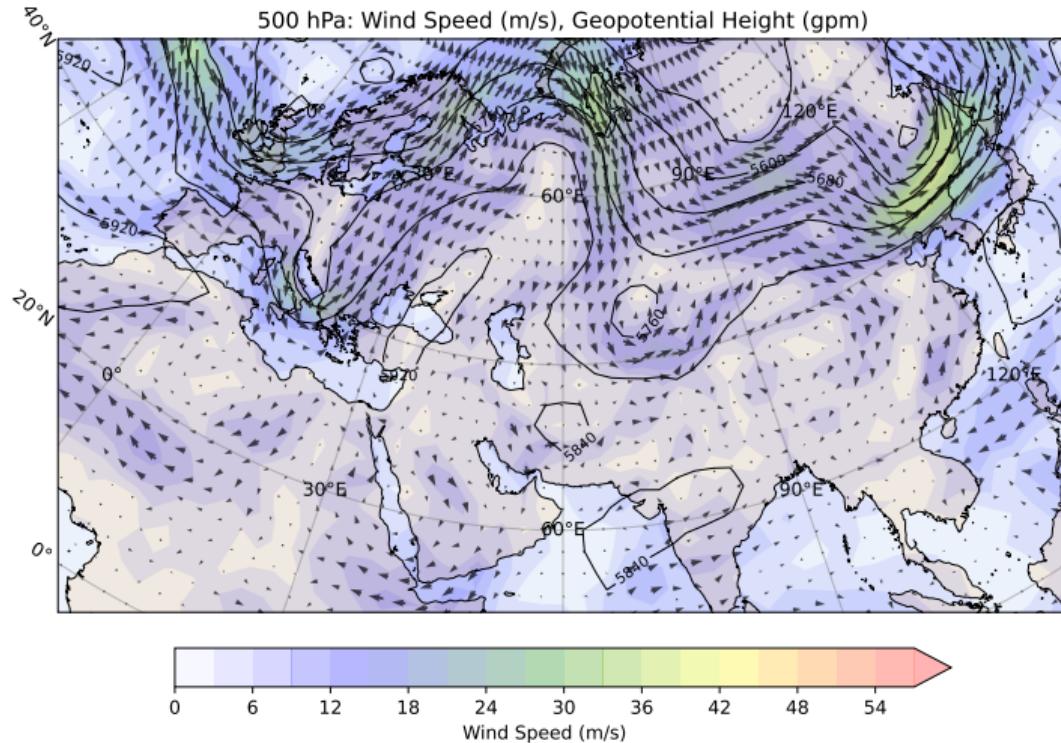
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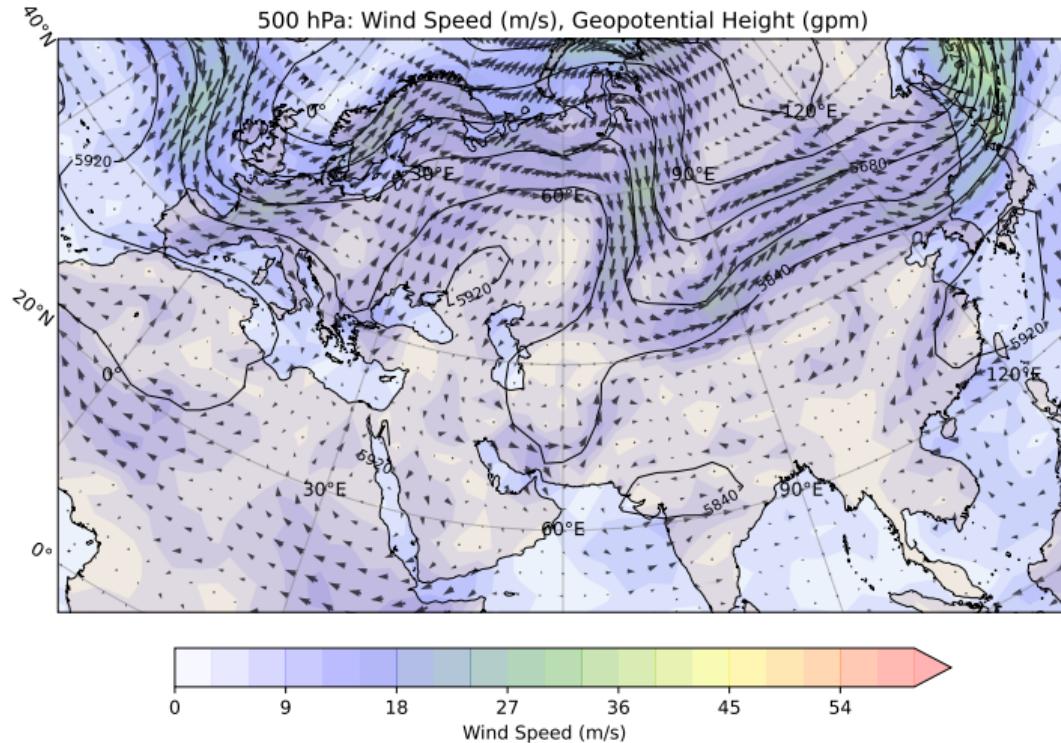
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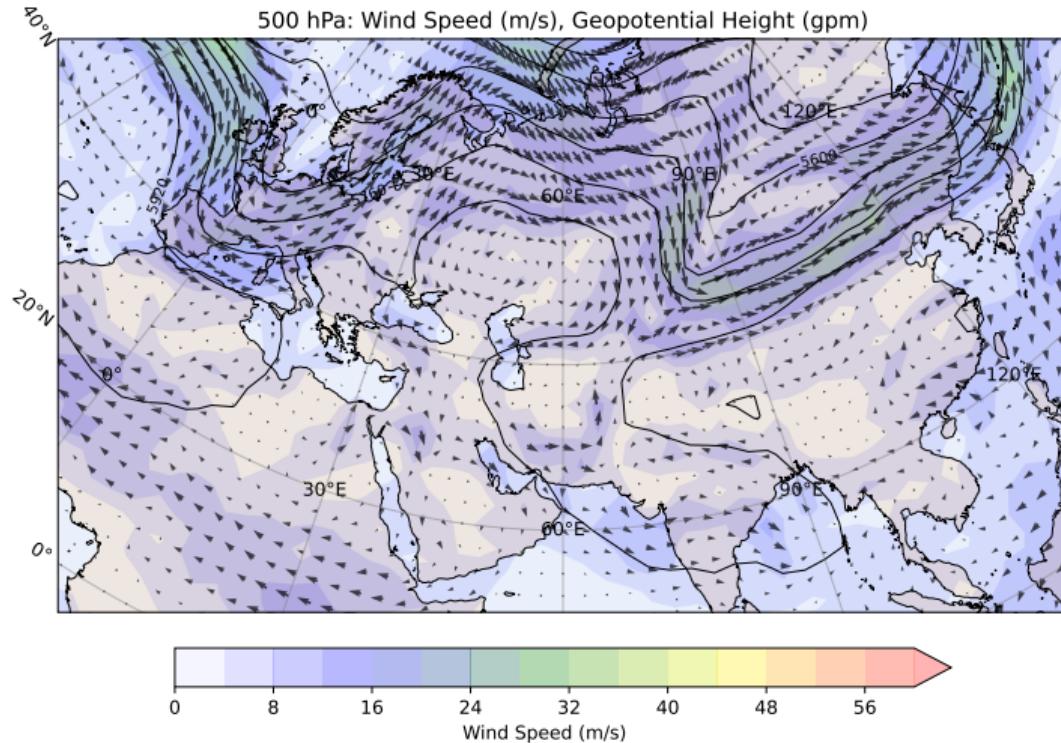
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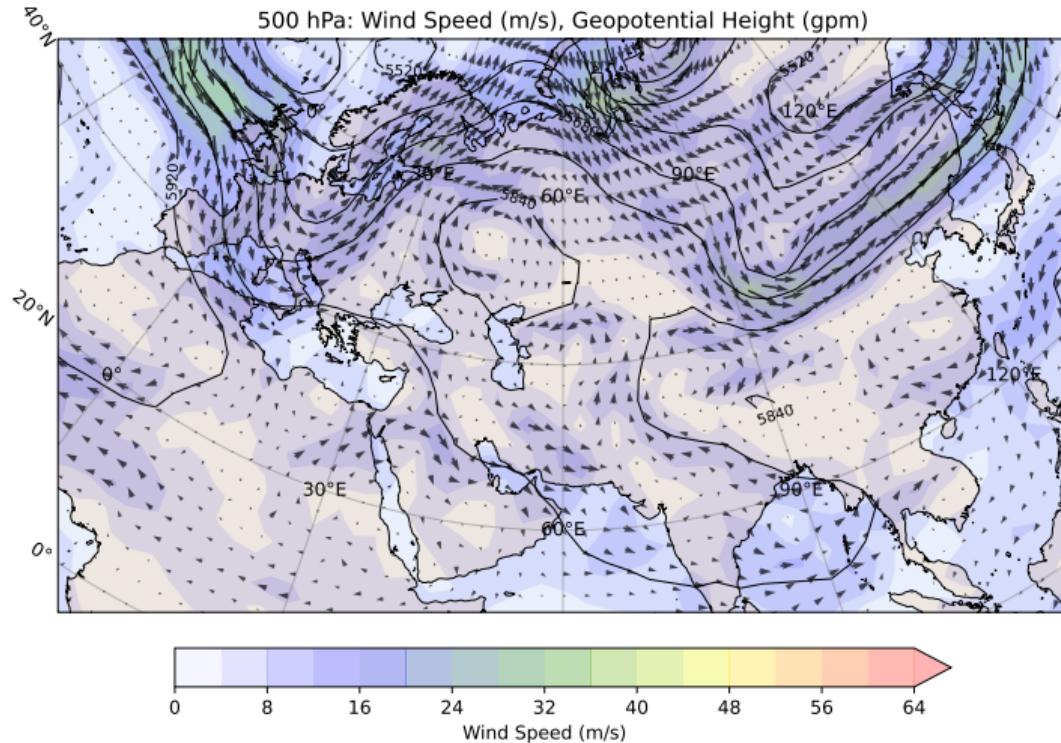
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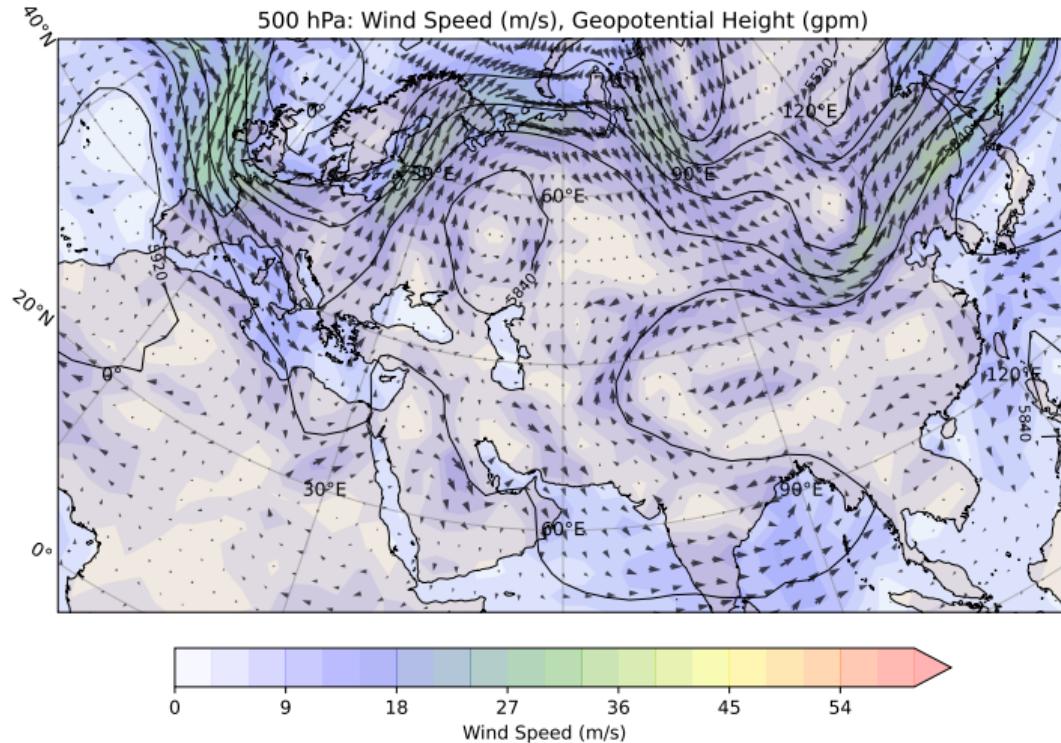
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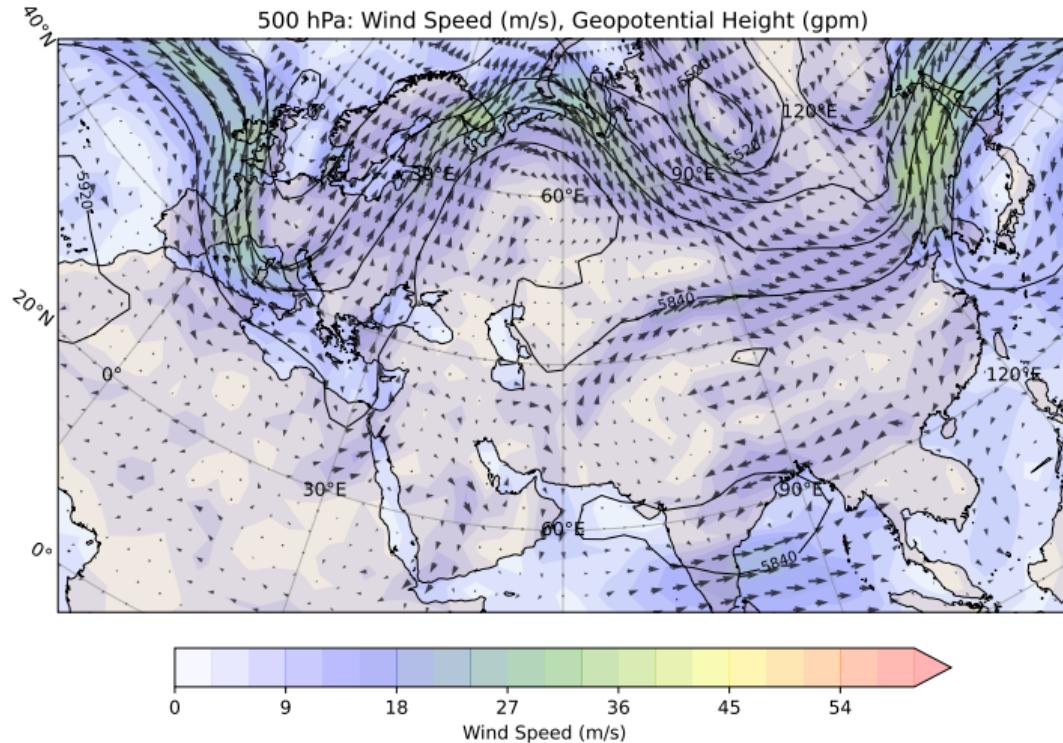
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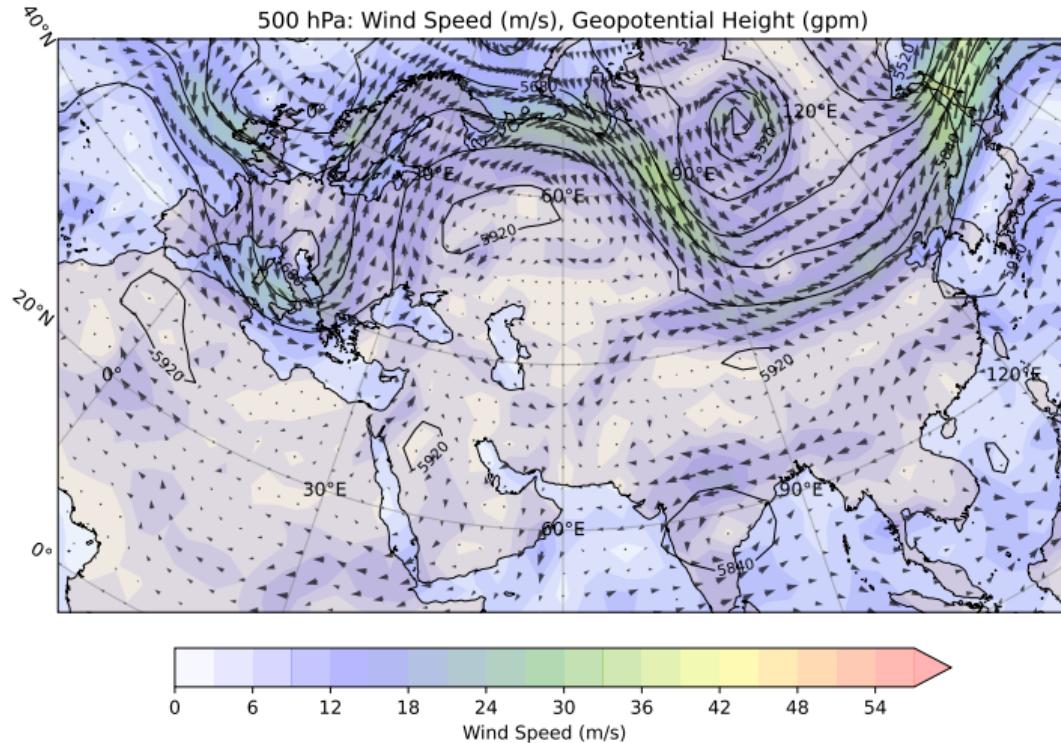
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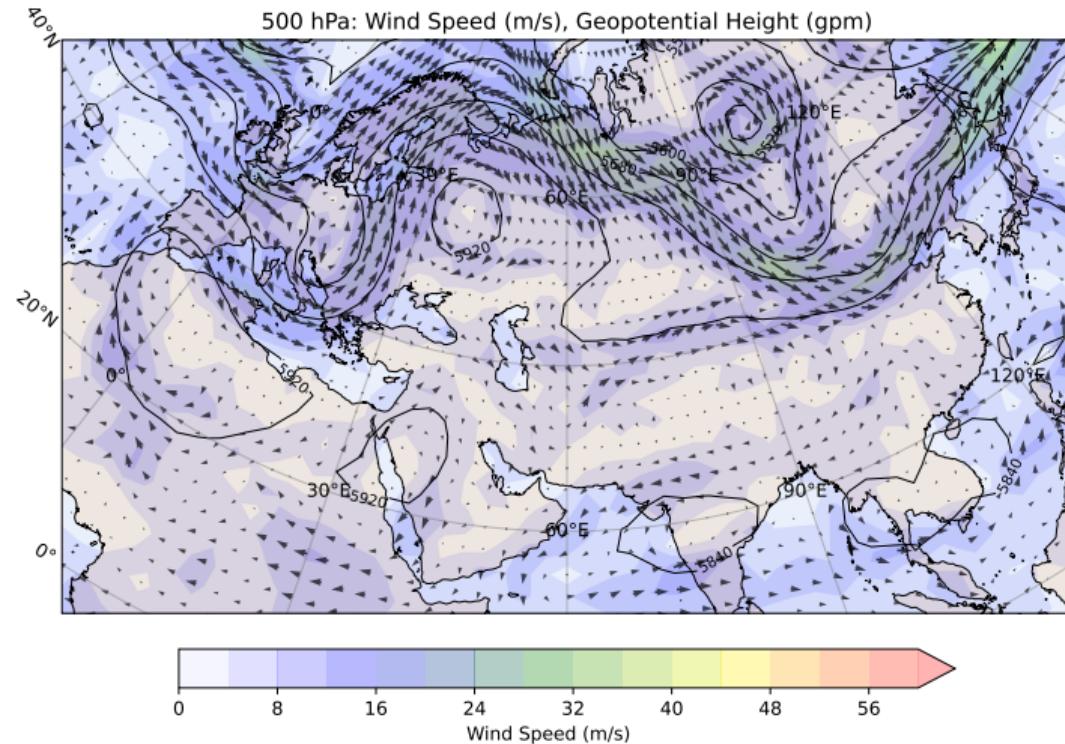
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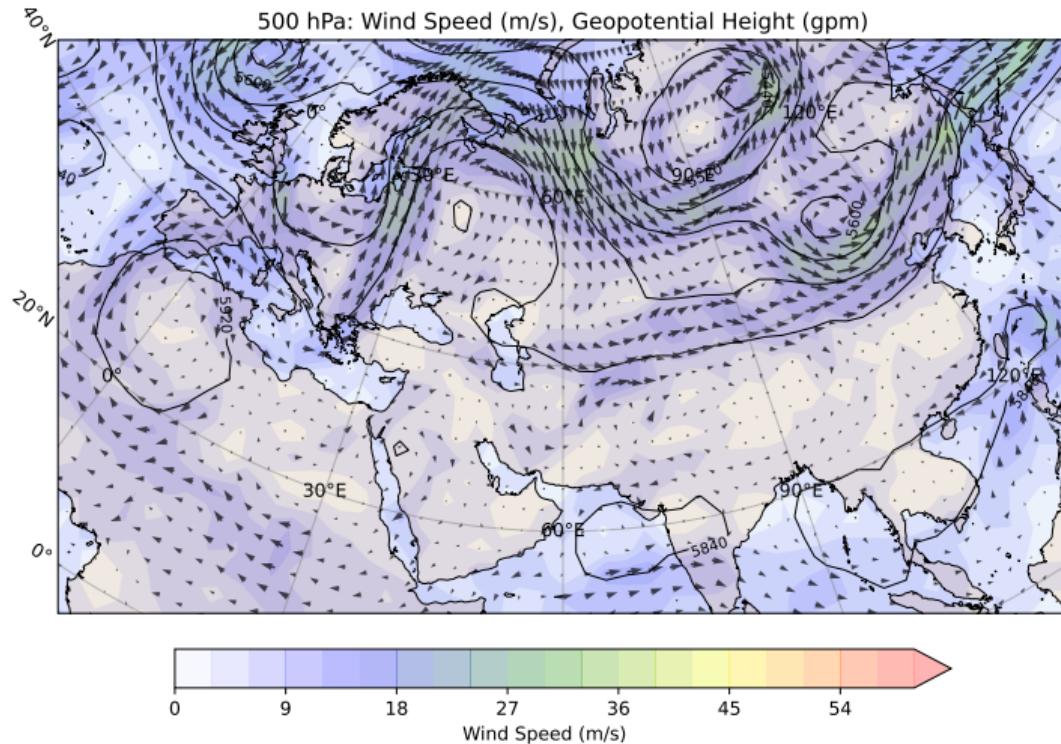
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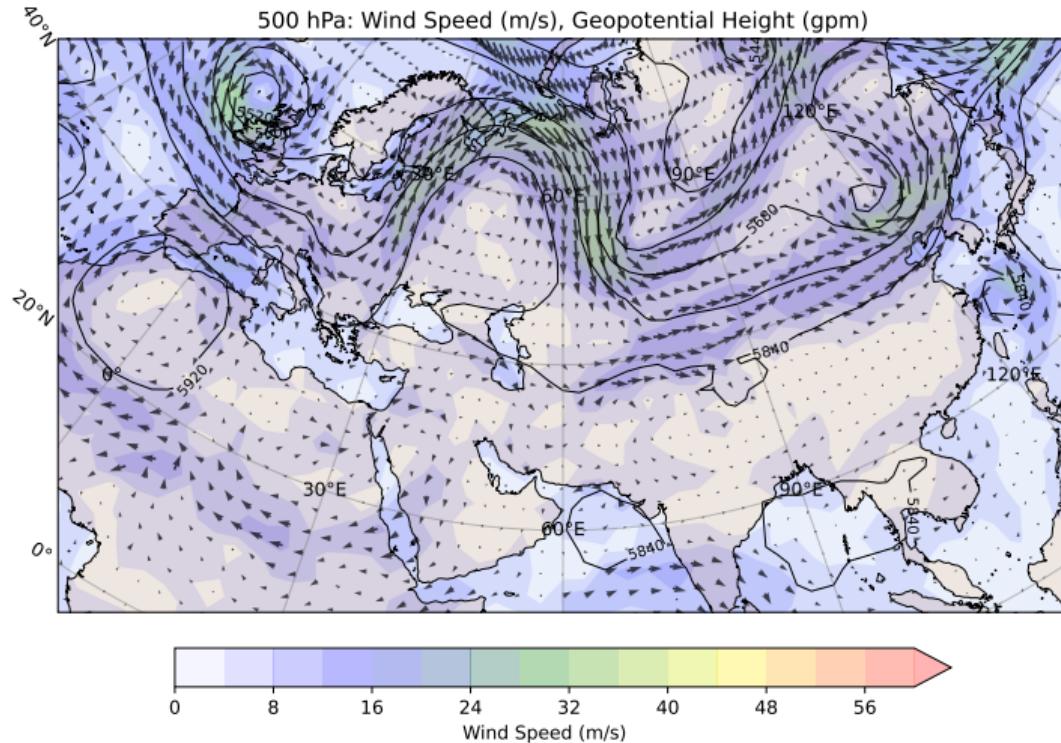
Forecast: 7-August-2010 at 12:00, Level 500hPa



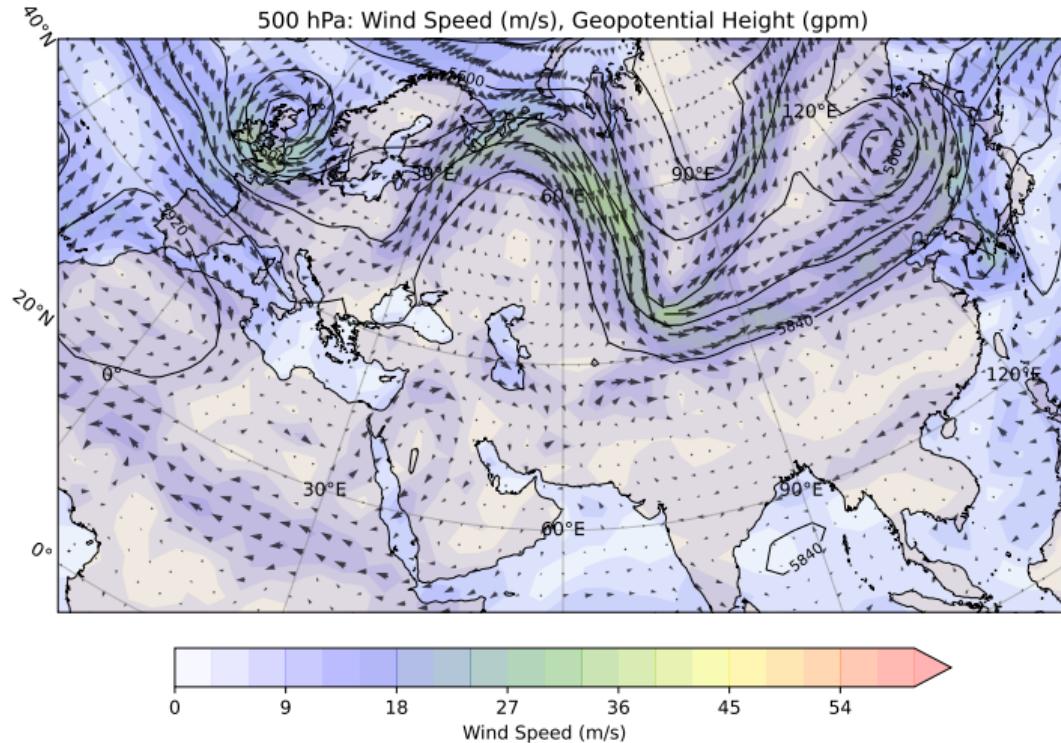
Forecast: 8-August-2010 at 12:00, Level 500hPa



Forecast: 9-August-2010 at 12:00, Level 500hPa



Forecast: 10-August-2010 at 12:00, Level 500hPa



Fragen

Fragen?

Referenzen

