Reply to Referee 3:

1. Line 11， line 304, what’s "3.15" super dust storm? -> should likely be: a super dust storm occurred in 15 March 2021 (hereafter “3.15” dust for short) ? I would not to use such kind of strange abbreviate.

Reply:

Thank you for your suggestion. The abbreviation "3.15" has been revised.

Revision:

p. 1, line 11: … and the economy. A super dust storm **occurred on 15 March 2021** raised Beijing's PM_{10}…

p. 14, line 304: … its intensity. For the super dust storm **occurred on 15 March 2021**, although the…

2. Introduction, mentioned some numbers of PM concentration, to avoid misleading you would better to clearly indicate how these numbers obtained, such as of the maximum concentration among station observation or as of the peak value in center of the system, or as of the means averaging over a specific region in north China or other region of interest.

Reply:

PM_{10} concentrations in line 32–33 in the introduction refer to **hourly observed PM_{10} concentrations**, cited from the article " Why super sandstorm 2021 in North China? " (Yin et al., 2022). The PM_{10} concentrations in line 60–61 represent the **daily maximum PM_{10} concentrations among station observations in North China** (34–42°N, 105–120°E), which are derived from China National Environmental Monitoring Centre. The corresponding concentrations are shown in Fig. S2. The explanation on how the PM_{10} concentrations were obtained has been added.

Related References:

Yin, Z. C., Wan, Y., Zhang, Y. J., and Wang, H. J.: Why super sandstorm 2021 in North China?, Natl. Sci. Rev., 9, nwab165, https://doi.org/10.1093/nsr/nwab165, 2022.

Revision:

p. 2, line 31–33: … an absence for more than 10 years in NC (Zhang et al., 2022). During 14–16 March 2021, the **hourly observed PM_{10} concentration** exceeded the monitoring threshold in Ulanqab (>9985 μg m^{-3}) and reached extraordinarily high value in Beijing (>7400 μg m^{-3}; Yin et al., 2022).

p. 2, line 58–62: … all instances of dust weather. According to **the daily maximum observed PM_{10} concentration in NC,** a dust event caused by a cold high resulted in a relatively low PM_{10} concentration of 1247 μg m^{-3} on 14 March 2023 (Fig. S1a). This event went largely unnoticed. However, on 22 March 2023, a severe dust storm, brought by a Mongolian cyclone (Fig. S1b), led to higher PM_{10} concentrations of 9993 μg m^{-3}, garnering more attention (Yin et al., 2023a).

3. Fig. 1b, is it more reasonable to show composite of cyclones and cold highs separately? Because the Mongolian cyclones and cold highs are not counterparts but independent in physics

Reply:

Thank you for your suggestion. The **composite results of PM_{10} concentrations** for MC and CH types are shown **separately** in **Fig. S3**. Figure 1b demonstrates the spatial distribution **differences** of composite PM_{10} concentrations for MC and CH types. This study focuses on **highlighting the differences in dust intensity** caused by the two types. Additionally, the **boxplots** of daily maximum hourly PM_{10} concentrations for the two types have been **separately** displayed in Fig. 1a. The emphasis on the differences in PM_{10} concentrations between the two types has been added to Section 3.

Revision:

p. 4, line 98: 3 PM_{10} concentration **differences** between regional synoptic systems

p. 4, line 123–126: There are **distinct differences in PM_{10} concentrations** between the MC and CH types. **Both** of the two types exhibited **high PM_{10}** concentrations in NC (**Fig. S3**). Compared to the CH type, the **MC type** resulted in **higher** PM_{10} concentrations and showed **more pronounced extremes** (Fig. 1a). The outliers in the PM_{10} concentration boxplot for MC type in Fig. 1a included the severe dust storms on March 15 2021, and March 22 2023… From the **spatial distribution differences** in PM_{10} concentrations, it can be observed that the MC type resulted in relatively **higher** PM_{10} concentrations in NC, especially in its northern region (Fig. 1b).

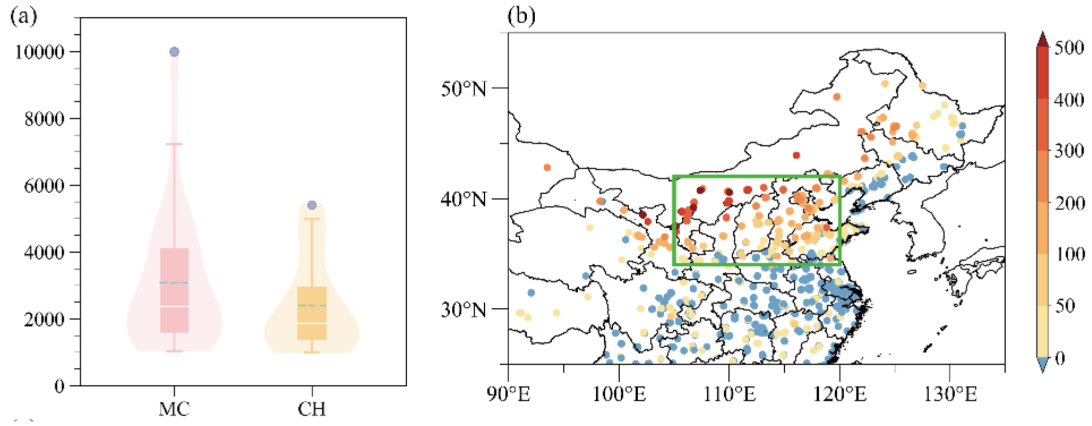

Figure 1. (a) Boxplots of daily maximum PM_{10} concentrations (units: μg m^{-3}) in NC during MC days (pink) and CH days (orange). The cyan dashed lines and blue dots in the boxplot represent average PM_{10} concentrations and outlier values. Density distributions of PM_{10} concentrations are shown by pink and orange shadings for MC days and CH days respectively. (b) The composite differences of observed daily maximum PM_{10} concentrations (scatter, units: μg m^{-3}) during MC days relative to CH days. The green box indicates NC.

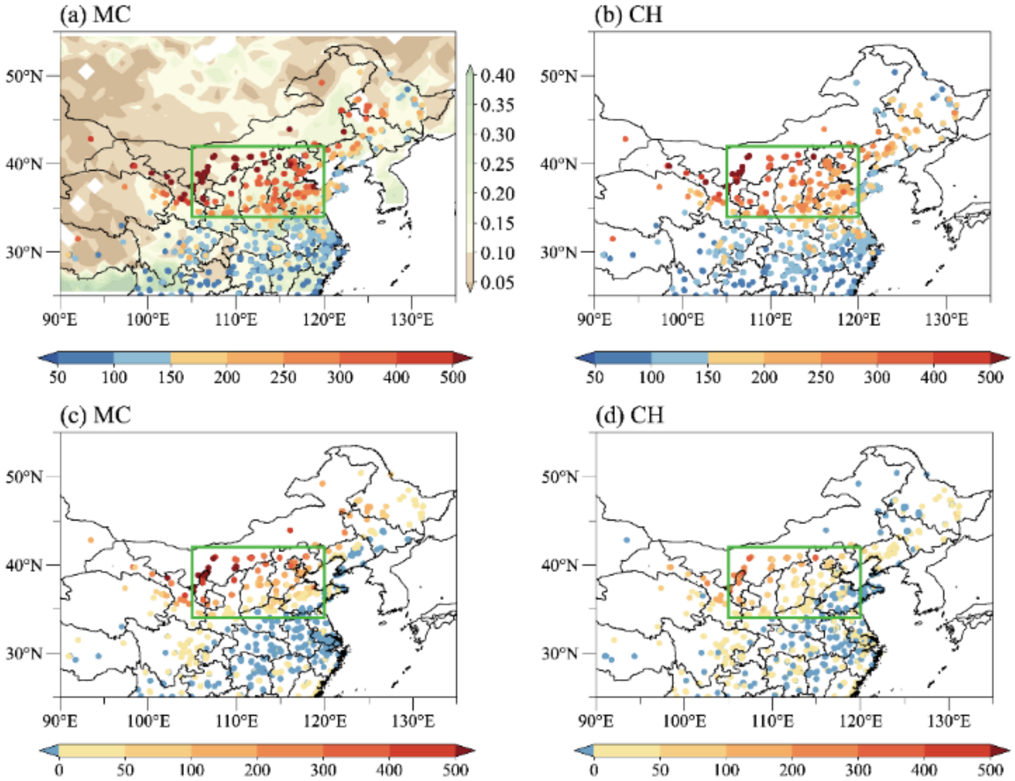

Figure S3. (a) Composite distribution of observed daily maximum PM_{10} concentrations (scatter, unit: μg m^{-3}) during MC days. Panel (b) is the same as (a) but for CH days. The shading in panel (a) indicates NDVI in March 2023. (c) Composite distribution of observed daily maximum PM_{10} concentrations anomalies (scatter, unit: μg m^{-3}) during MC days. Panel (d) is the same as (a) but for CH days. The green boxes in panel (a)–(d) represent NC.

4. Section 4, line 143-- , why talk anomalies in circulation relevant to synoptic cyclone and cold high? For example, readers may doubt the reality and reasonablity of the system if you talk typhoon in anomalous SLP fields. It seems better to show composites for original circulation field together with the anomalies, anyway, to avoid the possible confusing between the real synoptic system and the patterns exiting only in anomalous fields.

Reply:

We apologize for any misleading in our manuscript. The **identification of the Mongolian cyclone** and the **classification** of the two types of dust days are **based on the original SLP** circulation field, which has been **shown** in **Fig. S1**.

This study focuses on the **atmospheric circulation anomaly patterns** during dust weather occurrences under the influence of two synoptic systems. The anomaly fields provide a **clearer view of the circulation and meteorological conditions** associated with dust weather in North China. The **differences** in circulation between **the two types** can also be **clearly demonstrated** by anomaly fields. The previous wording in the article may lead to misunderstandings, so the revised version **emphasizes the anomalous conditions** of the circulation and **contrasts them with the original circulation fields** for analysis.

Revision:

p. 4, line 114: As depicted in the **original SLP fields** for the two types, the **main surface synoptic systems** for the two types of Dust days were the **Mongolian cyclone** and **cold high** respectively (Fig. S1c, d)….

p. 6, line 142: 4 Large-scale atmospheric circulation **anomalies**

p. 6, line 143–line 165: During Dust days of MC and CH types, there were strong **anomalous northerly winds** to the north of NC at the surface (**Fig. 2d, e**). During MC days, **due to the presence of the Mongolian cyclone** (**Fig. S1c**), there was a significant **negative SLP anomaly** in the eastern part of East Asia, with a **positive anomaly** in the west (Fig. 2a). The rear part of the **low-pressure anomaly** exhibited strong **anomalous northwest winds** (Fig. 2d). During CH days, the northern part of East Asia exhibited a significant **cold high-pressure anomaly**, with a **low-pressure anomaly** in the south (Fig. 2b). Between the two anomalous circulations, there were **northeasterly anomalous winds** to the north of NC (Fig. 2e). The **easterly wind anomaly**

components **weakened the westerly wind components** of the surface winds in the CH type. For CH days, the **actual wind** direction was **more northerly** compared to MC days (Fig. S1c, d) …

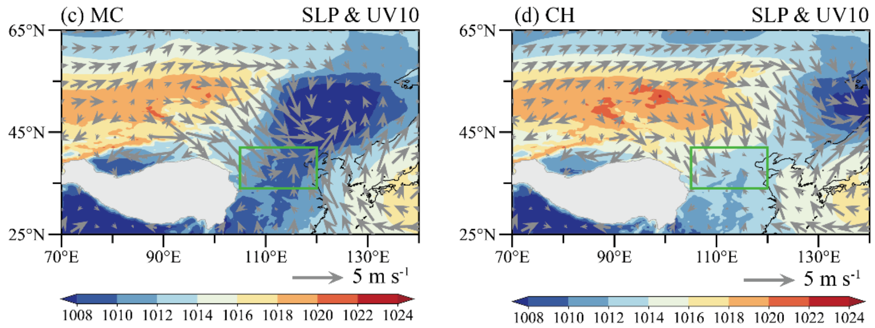

Figure S1. (c) **Composites** of **original SLP** (shading, units: hPa) and UV10 (vectors, units: m s^{-1}) during MC days. Panel (d) is the same as panel (c) but for CH days. The green boxes in panel (a)–(d) represent NC.

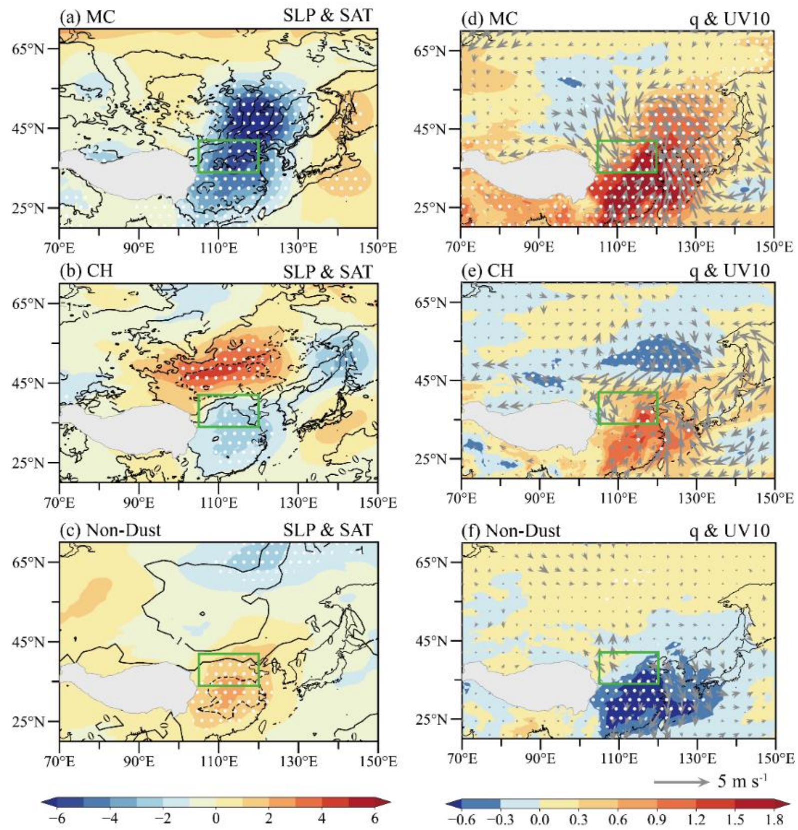

Figure 2. (a) **Composite anomalies** of SLP (shading, units: hPa) and SAT (contour, units: K) during MC days. White dots indicate that SLP anomalies exceed the 95% confidence level. Panel (b) and (c) are the same as panel (a) but for CH days and Non-Dust days. (d) Composite anomalies of q (shading, units: 10^{-3} kg kg^{-1}) and UV10 (vectors, units: m s^{-1}) during MC days. White dots indicate that q anomalies exceed the 95% confidence level. Panel (e) and (f) are the same as panel (d) but for CH days and Non-Dust days. The green boxes in panel (a)–(f) represent NC. S

5. Section 4, need to carefully clarify and refine. Synoptic processes and climate processes are combined/mixed. Case composites, as I see, are essentially synoptic configuration for multi-variables/fields, and can hardly to tell which is the cause and which is the effect.

Reply:

Section 4 has been **rewritten** with the following **modifications** based on the suggestions:

(1) We use composite analysis methods aimed at finding the common characteristics of synoptic processes. Section 4 in the previous manuscript analyzes from a synoptic perspective. **The revised manuscript mainly analyzes anomalous circulation conditions**. It explains the distribution of anomalous circulation fields, **their correlation with the original circulation fields**, and elucidates how **anomalous meteorological conditions can provide favorable conditions** for dust weather in North China.

(2) In the case composites, the configuration of multivariable fields is simultaneous, making it difficult to distinguish causality. **The revised Section 4 has primarily described the coexistence of anomalous conditions.** The anomalies in different atmospheric pressure levels are described **separately**. Additionally, the previous statement in Section 4 suggesting that mid-to-high-level troposphere circulation leads to the configuration of synoptic systems and meteorological conditions near the surface has been revised. In the **revised Section 5**, it is demonstrated through the calculation of **correlation coefficients** that there is a **correlation** between **anomalies in mid-to-high-level circulation** and **anomalies in near-surface circulation and meteorological conditions**.

Revision:

p. 6, line 143–line 165: … Although there were significant differences in the surface circulation anomaly patterns between the MC and CH types, some similar features could be observed in the mid to upper troposphere. The MC type and CH type **displayed intensified westerly winds** over the mid-latitude East Asia region at 200 hPa (Fig. 3a, b). At 500 hPa, both the MC and CH types **exhibited cyclonic anomalies** to the north of NC and anticyclonic anomalies to the east of NC (Fig. 3a, b). Compared to the CH type, the MC type showed stronger negative **geopotential height anomalies** at 500 hPa, with the center located in the northern part outside of NC (Fig. 3a). In contrast, the geopotential height anomalies to the north of NC at 500 hPa were weaker for the CH type (Fig. 3b). Since this 500 hPa cyclonic anomaly is located adjacent to the northern part of NC and over the sparsely vegetated external dust source area to the northwest of NC (Fig. S3a), we **hypothesize** that this **500 hPa cyclonic anomaly (CA)** is a **key anomalous circulation system** influencing dust activities in NC…

p. 10, line 230–line 240: The 500 hPa cyclonic anomaly (**CA**) and anticyclonic anomaly (ACA) circulation systems were **represented by** the 500 hPa geopotential height indices I_Z500c and I_Z500a (Table 1). While **I_Z500c** showed significant **correlations with other related meteorological indices**, it couldn't explain the anomalies in VATD and PBLH well on Dust days (Table 2). If only CA is considered, it may not be sufficient to provide the thermodynamic instability conditions for dust weather. When considering the role of **ACA**, it can be observed that **I_Z500a exhibited a stronger correlation with VATD and PBLH**, with correlation coefficients reaching 0.639 and 0.534, respectively (Table 2) … By considering CA and ACA together, calculating the difference in Z500 between them and normalizing it, the index I_ACA-CA was defined… Furthermore, **I_ACA-CA** exhibited **significant correlations** with **meteorological conditions** and **horizontal circulation** influencing dust weather in NC (Table 2), **consistent with** the physical mechanisms described in **Section 4**.

6. Dust are uplifted locally or transported into the region? Omega alone seems cannot explain why there are high PM concentration in both Mongolian cyclone and cold high cases, and the anomalous omega are also of very large scale extending toward the far west arid lands beyond the region of NC. Or simply caused by the horizontal wind speed at surface? Anyway, need to clarify the logics and consistence.

Reply:

(1) **This study primarily analyzes the transport of external dust to NC**. Previous studies have shown that **a significant portion** of the dust in NC **originates from external transport**, specifically from Outer Mongolia (Yin et al., 2022; Chen et al., 2023). 500 hPa cyclonic anomaly (**CA**) is located adjacent to the northern part of NC and **over the sparsely vegetated external dust source area** to the northwest of

NC. The analysis in this study confirms that the 500hPa cyclonic anomaly (CA), which is associated with the external dust transport into North China (NC), is the key anomalous circulation system. The **vertical circulation anomalies associated with CA** can provide **favorable conditions** for **dust emission** from the source areas and the **outward dispersion** of dust.

(2) For the **MC type**, the **zonal component** of vertical circulation anomalies is **more significant**. In the case of the **CH type**, the zonal component of vertical circulation anomalies is **weaker**, but the **meridional component** is more **pronounced**. The vegetation in the northwestern dust source areas is sparser compared to the northern regions, which may partially explain why the dust intensity of the MC type is greater than that of the CH type. In the revised version, we have **replaced Fig. 4b** and **Fig. 4e** with a **more significant vertical circulation anomalies** of the **meridional component** during **CH days**.

After **organizing the logic**, the relevant content has been **rewritten**.

Related References:

Chen, S. Y., Zhao, D., Huang, J. P., He, J. Q., Chen, Y., Chen, J. Y., Bi, H. R., Lou, G. T., Du, S. K., Zhang, Y., and Yang, F.: Mongolia Contributed More than 42% of the Dust Concentrations in Northern China in March and April 2023, Adv. Atmos. Sci., 40, 1549–1557, https://doi.org/10.1007/s00376-023-3062-1, 2023.

Yin, Z. C., Wan, Y., Zhang, Y. J., and Wang, H. J.: Why super sandstorm 2021 in North China?, Natl. Sci. Rev., 9, nwab165, https://doi.org/10.1093/nsr/nwab165, 2022.

Revision:

p. 6, line 166–line 178: … Since this 500 hPa cyclonic anomaly is located adjacent to the northern part of NC and over the **sparsely vegetated external dust source area to the northwest of NC** (Fig. S3a), we hypothesize that this 500 hPa cyclonic anomaly (CA) is a key anomalous circulation system influencing dust activities in NC. The vertical circulation structure of CA was further analyzed…

The **vertical circulation anomalies** associated with **CA** were primarily related to **the emission and transport of dust** from **the external dust source areas outside of NC**…

p. 8, line 191–line 198: The **east-west contrast** in the vertical structure of the CA was **weaker** for the **CH** type compared to the MC type (**Fig. S5a**), whereas the **north-south contrast** for the CH type was **more pronounced** (**Fig. 4b, e**). For the CH type, the **enhanced anomalous meridional vertical circulation** increased the importance of the **dust source areas to the north of NC** (Fig. S3a). The **vegetation cover** outside of NC along the **northern direction** was relatively **better** than that **along the northwest direction outside of NC**, indicated by higher NDVI (Fig. S3a). This might lead to **lower PM_{10} concentrations** in NC during CH days compared to MC days…

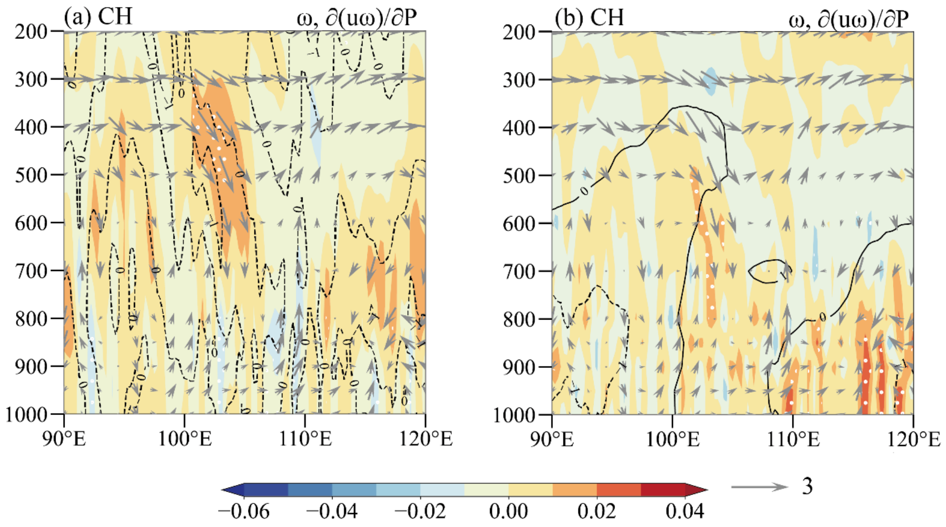

Figure S5. Composite anomalies of zonal component of the vertical circulation average over 40–60°N, 90–120°E during CH days: (a) The variables include ω (shading, units: Pa s^{-1}) and downward transport of westerly momentum (<0, dashed contour, units: 10^{-3} m s^{-2}). White dots indicate that ω anomalies exceed the 95% confidence level. The vectors represent ω (magnified 100 times) and zonal wind. (b) The variables include divergence (shading, units: 10^{-5} s^{-1}) and q (contour, units: 10^{-4} kg kg^{-1}). White dots indicate that divergence anomalies exceed the 95% confidence level. The vectors represent ω (magnified 100 times) and zonal wind.

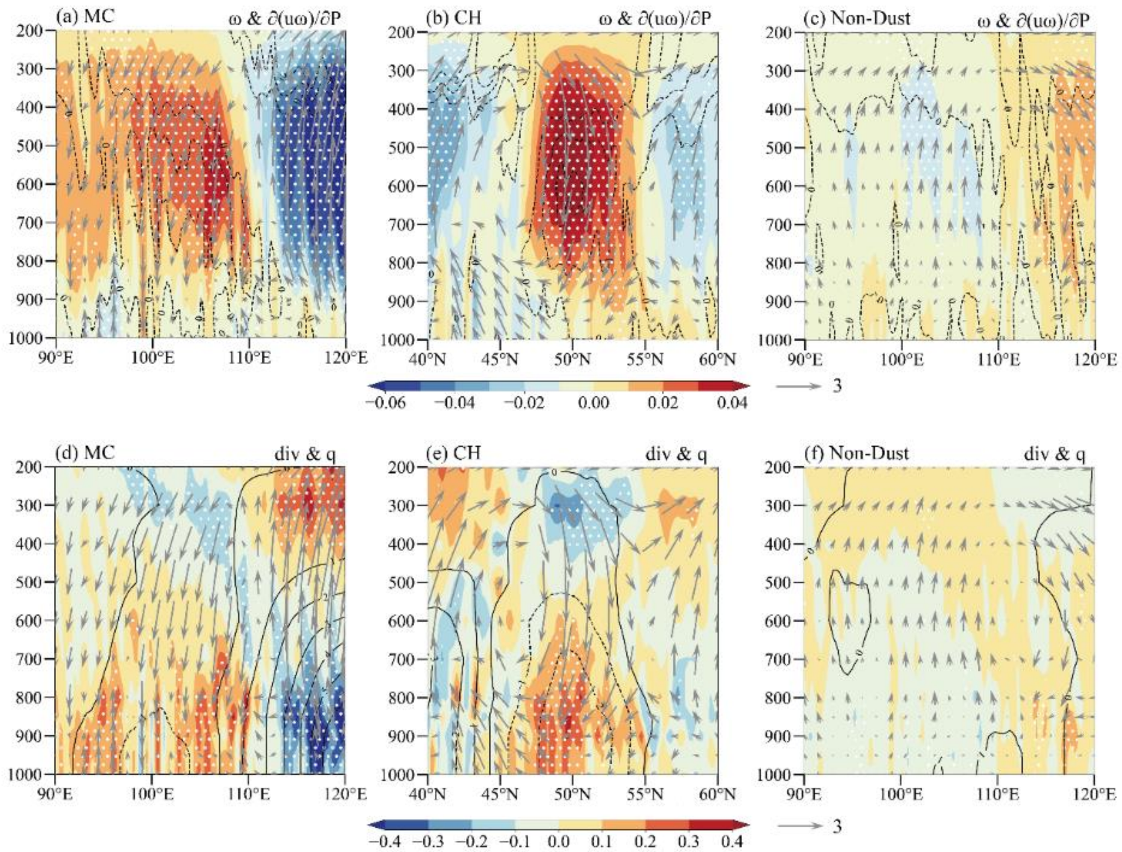

Figure 4. Composite anomalies of zonal component of the vertical circulation average over 40–60°N, 90–120°E during MC days: (a) The variables include ω (shading, units: Pa s^{-1}) and downward transport of westerly momentum (<0, dashed contour, units: 10^{-3} m s^{-2}). White dots indicate that ω anomalies exceed the 95% confidence level. The vectors represent ω (magnified 100 times) and zonal wind. (d) The variables include divergence (shading, units: 10^{-5} s^{-1}) and q (contour, units: 10^{-4} kg kg^{-1}). White dots indicate that divergence anomalies exceed the 95% confidence level. The vectors represent ω (magnified 100 times) and zonal wind. Panel (c) and (f) are the same as panel (a) and (d) respectively, but for Non-Dust days. Composite anomalies of meridional component of the vertical circulation average over 40–60° N, 90–120° E during CH days: (b) The variables include ω (shading, units: Pa s^{-1}) and downward transport of westerly momentum (<0, dashed contour, units: 10^{-3} m s^{-2}). White dots indicate that ω anomalies exceed the 95% confidence level. The vectors represent ω (magnified 100 times) and meridional wind. (e) The variables include divergence (shading, units: 10^{-5} s^{-1}) and q (contour, units: 10^{-4} kg kg^{-1}). White dots indicate that divergence anomalies exceed the 95% confidence level. The vectors represent ω (magnified 100 times) and meridional wind.

7. Fig.2, Z500 and U200, I would like to suggest authors to change legend, say, Z500 shown in contour lines, so helpful to demonstrate mid-troposphere trough and ridge, and helpful to explain near surface cyclone before the trough/behind the ridge.

Reply:

Thank you for your suggestion. The **legend** for **Figure 2 (a)–(c)** has been **changed**. In the revised version, **Z500** is shown in **contour lines (Fig. 3)**. The mid-tropospheric trough and ridge are well depicted in the modified version, contrasting with the original circulation field of Z500 **(Fig. R1)**.

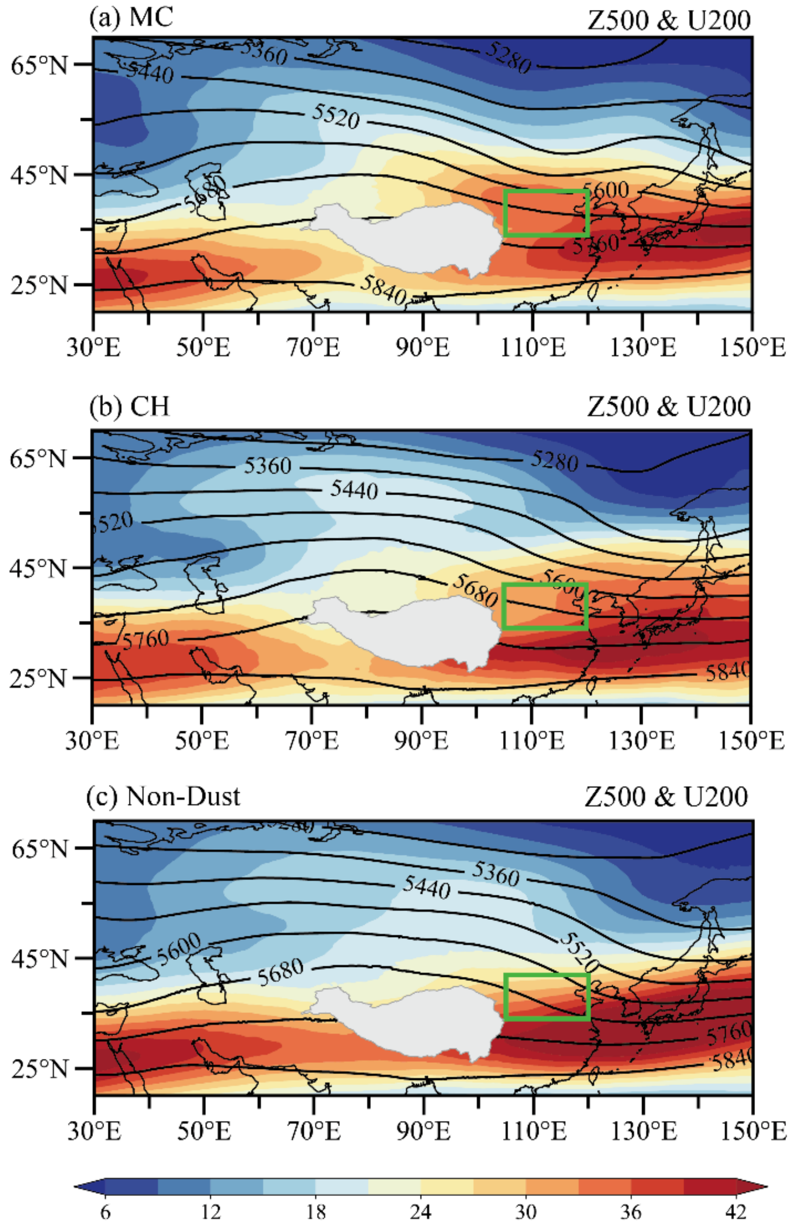

Figure R1. (a) Composites of **Z500** (**contour**, units: geopotential meter, gpm) and U200 (shading, units: m s^{-1}) during MC days. Panel (b) and (c) are the same as panel (a) but for CH days and Non-Dust days. The green boxes in panel (a)–(c) represent NC.

Revision:

p. 7, line 179–line 184:

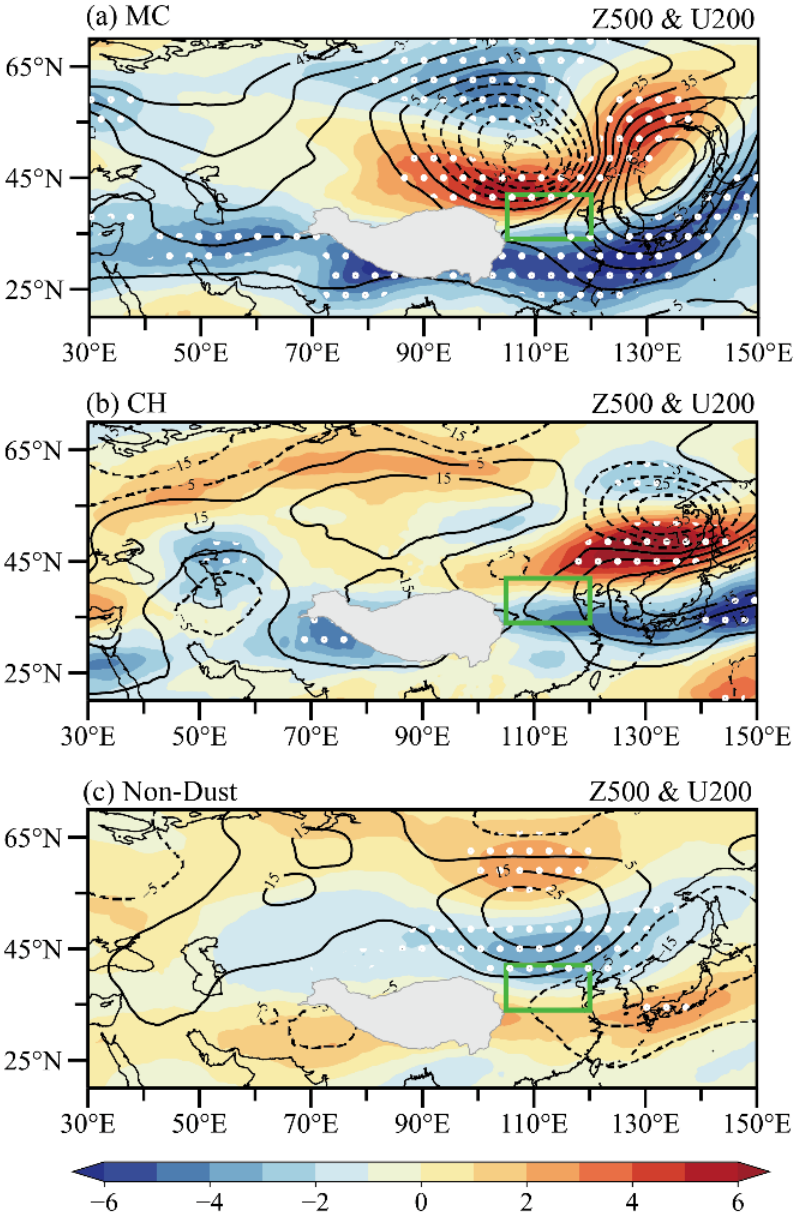

Figure 3. (a) Composite anomalies of **Z500** (**contour**, units: geopotential meter, gpm) and U200 (shading, units: m s^{-1}) during MC days. White dots indicate that U200 anomalies exceed the 95% confidence level. Panel (b) and (c) are the same as panel (a) but for CH days and Non-Dust days. The green boxes in panel (a)–(c) represent NC.

8. Section 5, all predictors are simultaneous fitting variables identified in composite analysis. Readers may find of interest if you demonstrate how the cyclone and cold highs generates/develops/moves/strengthens and construct a set of predictor and predicting the dust in advance accordingly.

Reply:

In Section 5, based on simultaneous variables and correlation analysis, we found that the 500hPa cyclonic anomaly (**CA**) and anticyclonic circulation anomaly (**ACA**) are **important anomalous circulation systems** influencing the two types of dust weather in North China. Therefore, we propose **a common predictor**, I_ACA-CA, for the two types of dust weather. I_ACA-CA provide a reference for **seasonal prediction** of dust weather. The ability of the **C3S seasonal forecast model** to reproduce I_ACA-CA was further assessed. The I_ACA-CA calculated by **ECMWF, DWD, and MF** seasonal forecast models **with a one-month lead captured 46.1%, 52.2%, and 51.3% of spring dust days** when positive.

In addition, I_ACA-CA shows a dust signal two days in advance of dust days, capturing **56.5%, 69.6%,** and **76.5%** of dust days two days in advance, one day in advance, and on the dust day, respectively. **The evolution of CA, ACA and related atmospheric circulation anomalies before** MC days and CH days was **further investigated** (**Fig. 7**). **The movement and development of the Mongolian cyclone and the cold high before** the two types of dust days are also **depicted through the original circulation field** (**Fig. S7**). The development and movement of CA and ACA aligned with the occurrence and development of MC days and CH days in NC. The common predictor I_ACA-CA served as a meaningful indicator for predicting dust weather in NC.

Based on the above, we have **reorganized the logic** of Section 5 and **rewritten** it.

Revision:

p. 10, line 217–line 267:

… In order to **comprehensively predict dust weather** of the MC and CH types, we **defined a series of meteorological indices** to **explore the common anomalous circulation systems** influencing these two dust weather types… **I_ACA-CA is designated as a common predictor for the two types of Dust days in NC**… In correspondence with the positive I_ACA-CA observed **two days, one day (I_ACA-CA>its one standard deviation), and zero day (I_ACA-CA>its one standard deviation) in advance**, successful **capture rates of 56.5%, 69.6%, and 76.5% for Dust days** were achieved. These high percentages suggest that the reinforced positive I_ACA-CA significantly contributed to the high PM_{10} concentrations in NC.

The **evolution** of **CA, ACA** and related atmospheric circulation anomalies **before MC days and CH days** was further investigated (Fig. 7). Prior to both types of Dust days, CA and ACA **moved** eastward towards NC (Fig. 7). For MC type, CA and ACA from western Siberia and Lake Baikal gradually **strengthened** as they moved eastward (**Fig. 7a–d**). **The development of the Mongolian cyclone** intensified (**Fig. S7a–d**), accompanied by an eastward strengthening of the associated surface low-pressure anomaly and cyclonic winds to the northwest of NC (Fig. 7a–d). As the surface low pressure anomaly moved eastward, the anomalous southerly winds north of NC shifted to anomalous northerly winds (Fig. 7c, d). The **actual wind** directions **changed** from westerly to northwesterly (Fig. S7c, d). For CH type, CA and ACA were relatively positioned more to the east (Fig. 7e), with CA moving eastward from central Siberia and gradually weakening, while ACA moving eastward from Northeast Asia gradually strengthened (Fig. 7e–h). **The cold high intensified as it moved eastward** (Fig. S7e–g), accompanied by an eastward strengthening of the surface high-pressure anomaly (Fig. 7e–g). **One day before** the CH-type dust day, the surface high-pressure anomaly **replaced** the low-pressure anomaly to the north of NC (Fig. 7g, h), and the wind anomalies north of NC **shifted** from southwest to northeast (Fig. 7f–h). The actual wind directions **changed** from westerly to northerly directions (Fig. S7f–h). In summary, the development and movement of CA and ACA aligned with the occurrence and development of MC days and CH days in NC. The common predictor I_ACA-CA served as a meaningful indicator for predicting dust weather in NC.

p. 13, line 293–line 295: … The I_ACA-CA calculated by **ECMWF, DWD, and MF seasonal forecast models** with a one-month lead captured around 50% of spring dust days when positive.

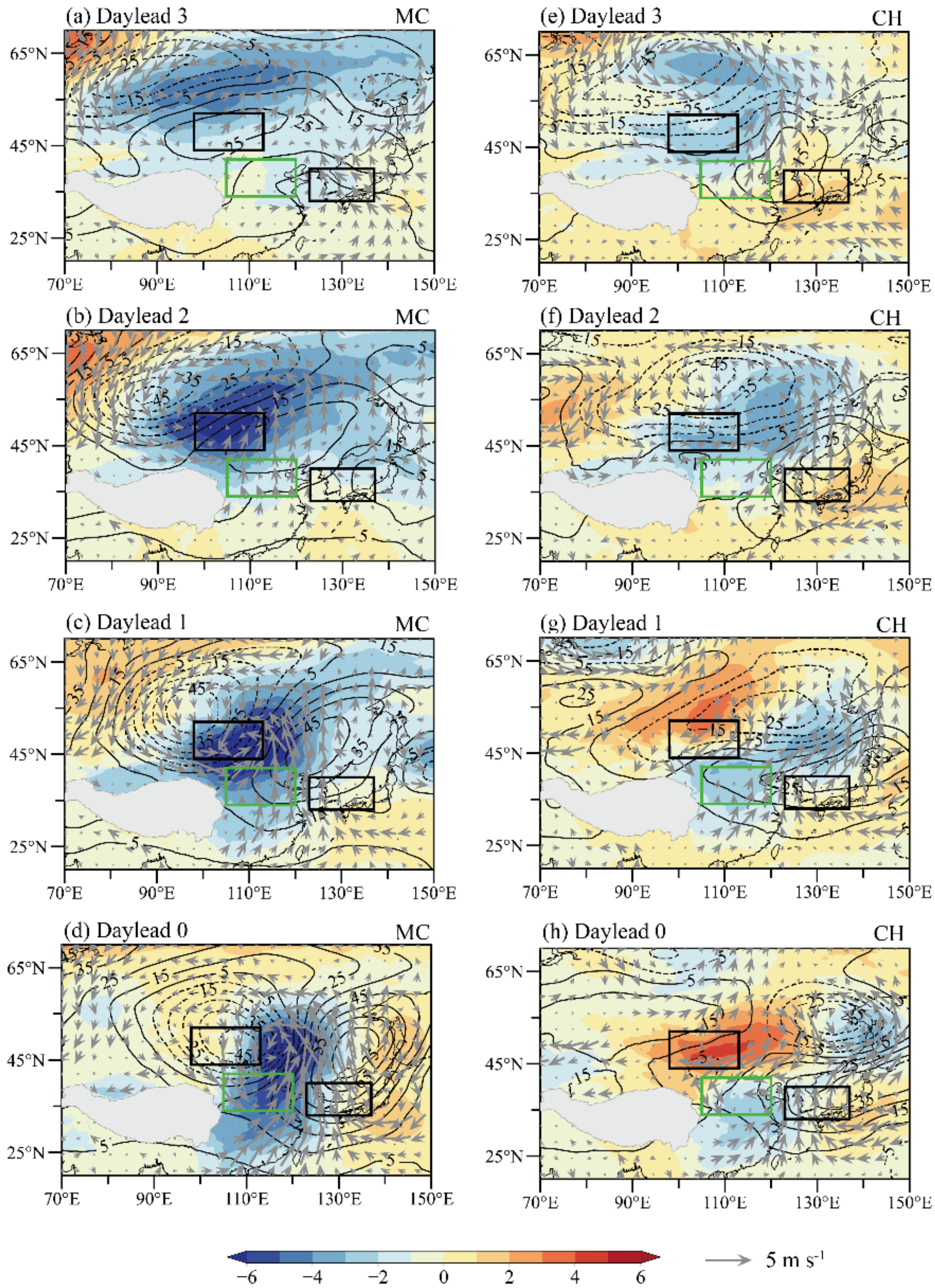

Figure 7. (a)–(d) Lead composite evolution of Z500 (contour, unit: gpm) anomalies, SLP (shading, unit: hPa) anomalies, and UV850 (vectors, units: m s^{-1}) anomalies during MC days. Panel (e)–(h) are the same as panel (a)−(d) but for CH days. The green boxes in panel (a)–(h) represent NC, while the black boxes represent the region for calculating I_ACA-CA.

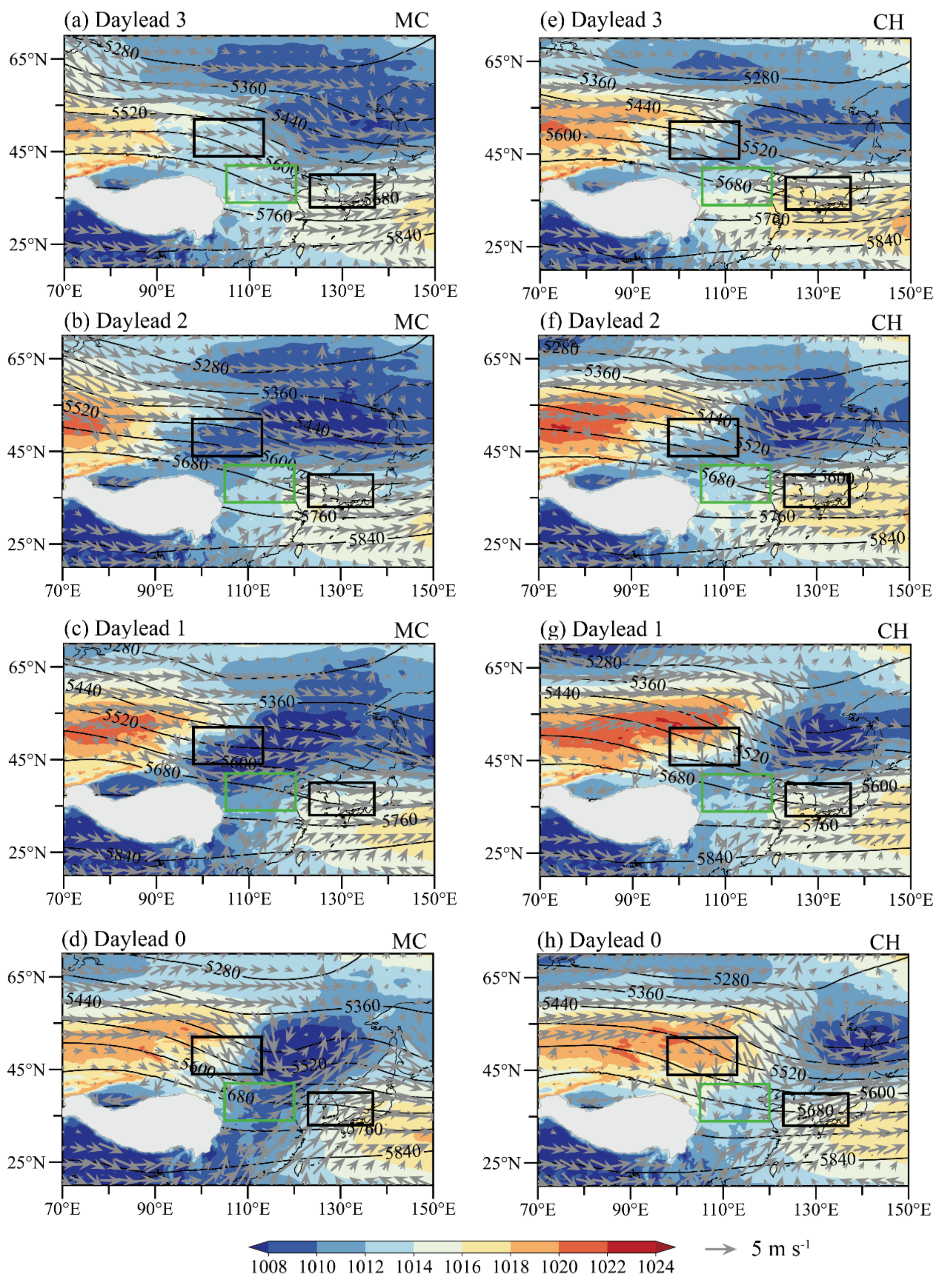

Figure S7. (a)–(d) Lead composite evolution of original Z500 (contour, unit: gpm), SLP (shading, unit: hPa), and UV850 (vectors, units: m s^{-1}) during MC days. Panel (e)–(h) are the same as panel (a)–(d) but for CH days. The green boxes in panel (a)–(h) represent NC, while the black boxes represent the region for calculating I_ACA-CA.