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Study on Diagnosis Weather Process and Flight Impact of Heavy Snowfall in Northeast China "11/2021"

Xiaohui Zhang, Hengrui Tao, Ying Zheng

College of Aviation Operations Service, Air Force Aviation University, Changchun, China
Email: zxh_atmosphere@yeah.net

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Abstract

Based on ERA5 reanalysis data, the characteristics of weather situation, water vapor condition, dynamic uplift condition, energy condition, ice accumulation environment and flight effect of aircraft in the heavy snowfall process in northeast China from November 5 to 12, 2021 are analyzed. The results show that the heavy snowfall process in Northeast China is caused by the combination of Northeast China Cold Vortex, trough, low level frontal cyclone and cold front. Through the analysis of the physical field, it is found that the sufficient water vapor transport is from the south and the southeast, the convergence rising in the lower layer, divergence "pumping" in the upper layer, air flow rising in the vertical plane and a large amount of convection effective potential energy are all contributing to the heavy snowfall. The impact of heavy snowfall on flight mainly includes low visibility and ice accumulation. Water vapor flux, water vapor flux divergence, vertical velocity, potential temperature and convective effective potential energy can all be used as the judging indexes of heavy snowfall forecast.

Keywords

Heavy Snow, Weather Situation, Water Vapor, Energy, Aircraft Icing

1. Introduction

In recent years, extreme weather events have been frequently occurred and their antennae have been extended to many regions in the world. Record heavy rains, droughts, and high temperatures have been frequently visited around the world. The extreme weather events of the past decades, or even of a century, are becoming the new normal. In 2021, China's weather situation is complicated, the climate is remarkable, and extreme events occur frequently. Henan and Shanxi have seen very rare heavy rain since meteorological records; the northern heavy snowfall in early November added an extraordinary footnote to the annual climate.

In early November 2021, the widespread rain and snow disaster was an extreme weather event caused by the effects of climate warming and the "double La Nina". La Niña is a condition in which the ocean is unusually cold in the central and eastern Pacific Ocean. When affected by La Niña, the SST in the equatorial eastern Pacific is lower than 0.5˚C, which causes the Meridional circulation anomaly in East Asia, which is favorable for the cold air in the north of China to descend southwards, and then causes the winter in China to be colder than usual. In the autumn and winter of 2020-2021, La Niña occurred in our country, and in October 2021, a weak to medium intensity La Niña occurred in winter, that is, two consecutive winter years of "double peak La Niña", so the heavy snowfall occurred in the year of "Double Lana".

Heavy snowfall is the main winter weather phenomenon in northern China, and it is also a disastrous weather that affects flight safety. At present, many scholars at home and abroad have studied the formation mechanism of heavy snowfall, the characteristics of climate distribution and the forecasting methods. The reason of snowfall in China is analyzed from many aspects, such as weather system, water vapor condition, troposphere high and low altitude configuration, dynamic mechanism and temperature advection. Some studies indicate that snowfall area in North Xinjiang is related to mesoscale weather system and blackbody bright temperature, while the mechanism of snowstorm in South Xinjiang is similar to summer rainstorm, which is often caused by the combined action of Tashkent low vortex and ground backflow cold air (Zhang et al., 2013; Liu et al., 2011). Some analysis shows that a short-time strong snowfall process in Northeast China is related to the lower front generation, topographic circulation, favorable distribution of divergent field and unstable energy released by the rising motion induced by wind shear at low altitude (Jiao et al., 2021). Some analysis shows that spatial distribution of snow in the west of Southern Xinjiang is uneven, and the average annual snowfall is increasing based on the daily precipitation data of 17 meteorological stations in the west of Southern Xinjiang analyzed the spatial distribution, inter annual variation and its persistent characteristics of snow in the west of Southern Xinjiang in the past 50 years (Nurbia et al., 2016). The snowfall in Northeast China can be divided into pure snow snowfall and rain-snow mixed snowfall. The snowfall varies greatly from year to year and has obvious decadal characteristics (Chen et al., 2012). Some scholars established a snowfall forecasting model by studying 10 typical rain-snow weather processes in Hangzhou (Li et al., 2020). Some scholars used four cloud microphysical schemes of WRFV3.5.1 to simulate the snowstorm process caused by a severe cold tide in Xinjiang, and explore the influence of different cloud microphysical schemes on the prediction results (Yu et al., 2017).

At present, the research scope of heavy snowfall is very wide, but there are few studies of heavy snowfall in the background of "double La Nina Year" in Northeast China. So this paper makes use of the spatial resolution 0.25˚ × 0.25˚ ERA5 hourly reanalysis data issued by European Medium-term Weather Forecast Center, starting with snowfall fact, circulation situation, formation mechanism, formation mechanism, etc., to provide reference for snowfall prediction period from 04 to 12 in November 2021.

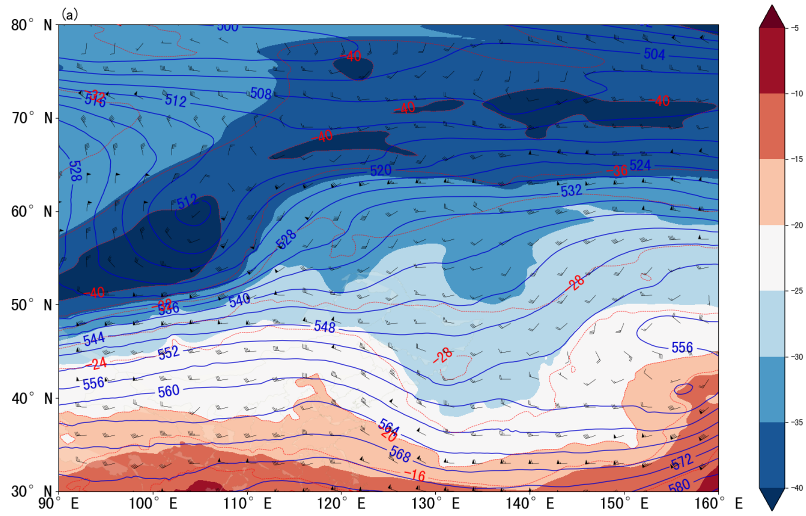
2. Analysis of Snow Process in "11/2021"

2.1. Analysis of Weather Situation

In early November, the cold air accumulated and merged with the cold air in the Siberian low pressure trough south, then encountered the Qinghai-Xizang Plateau and Pamir Plateau to block the low pressure. With the southern impact of a cold air, the low pressure trough was cut off and formed a cold vortex system. On November 4, a large amount of polar cold air was carried into many places in China (**Figure 1(a)**). From November 4 to 12, there was an obvious process of cold air descending southward on 500 hPa weather map (**Figure 1(a)** and **Figure 1(b)**), which caused cold wave influence in Inner Mongolia, Northeast China and other places. On November 7, the cold front (medium blue shadow area is cold air in **Figure 1**, cold air meets south warm air in the south of Jianghuai area), and then meets south warm air in the south of Jianghuai (**Figure 1**). Analysis of the upper air map of November 4 - 12 shows that the cold center (red isotherm) in the northeast region appears in combination with the low pressure center (blue isotherm) on the 500 hPa weather map, the northeast region is affected by the cold vortex for a long time (**Figure 1(b)** and **Figure 1(c)** and **Figure 1(d)**), and the cyclone curvature of the contour in the northeast cold vortex region (blue solid line) can be obviously analyzed. On the 850 hPa and 700 hPa high air maps, most areas in the northeast are also in front of the warm and the steam flow is in the warm and wet water are also provided. Analyzing the weather situation during the heavy snowfall, the low, middle and high altitude are affected by the trough, the south warm and wet air in front of the trough and the front cyclone carry a large amount of warm and wet air in the north provide sufficient water vapor conditions for the strong snowfall. The front cyclone converges in the near ground layer. The northeast cold vortex rises slowly eastward and makes the strong upward force for the near ground layer.

2.2. Snow Facts

From November 5 to 12, 2021, snow continued in the southeast region of Inner Mongolia, Beijing, Tianjin, Hebei and Northeast regions, resulting in the maximum wind gusts of 9 - 10 grade due to the continuous development of the front cyclone. On November 6, a banded snow area was observed in China from north to south (**Figure 2(a)**). On November 7, at 08, the snow area increased and moved northward until the 12th day. This snowfall process is intense and has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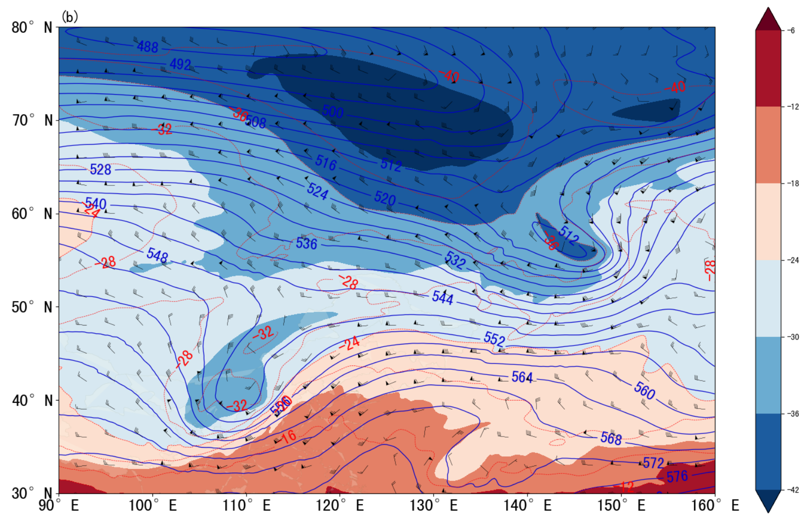
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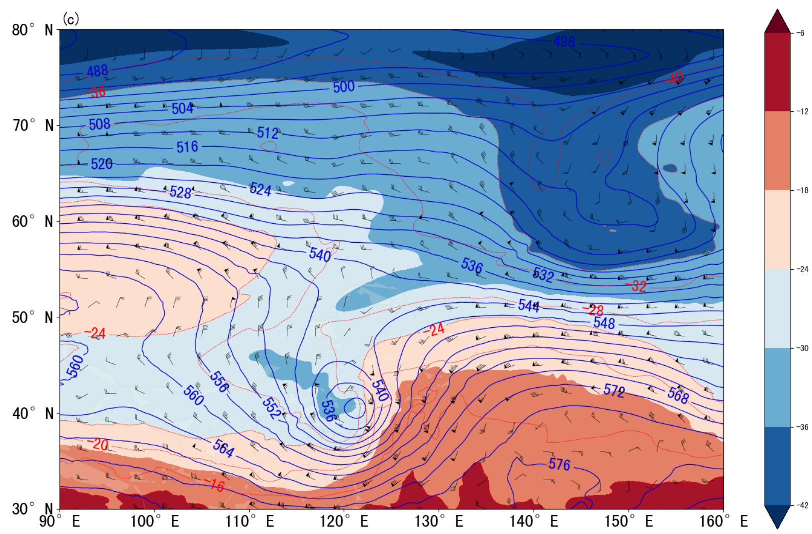
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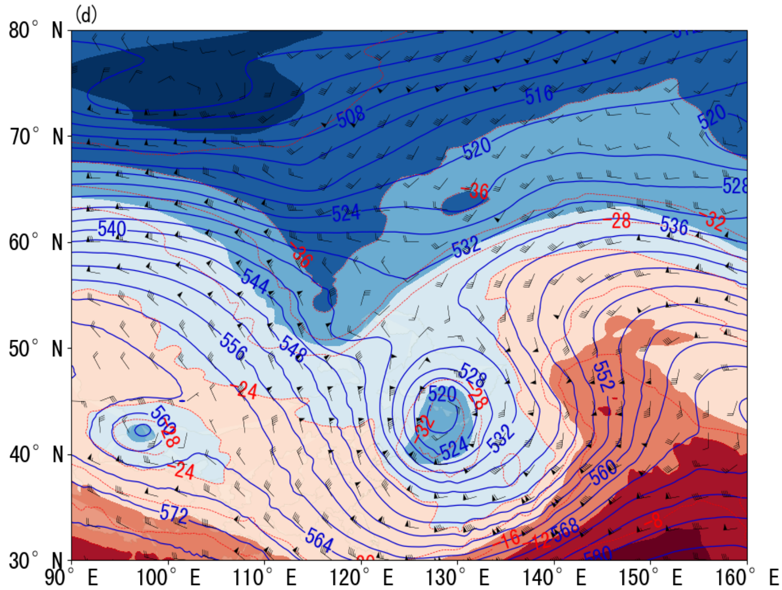
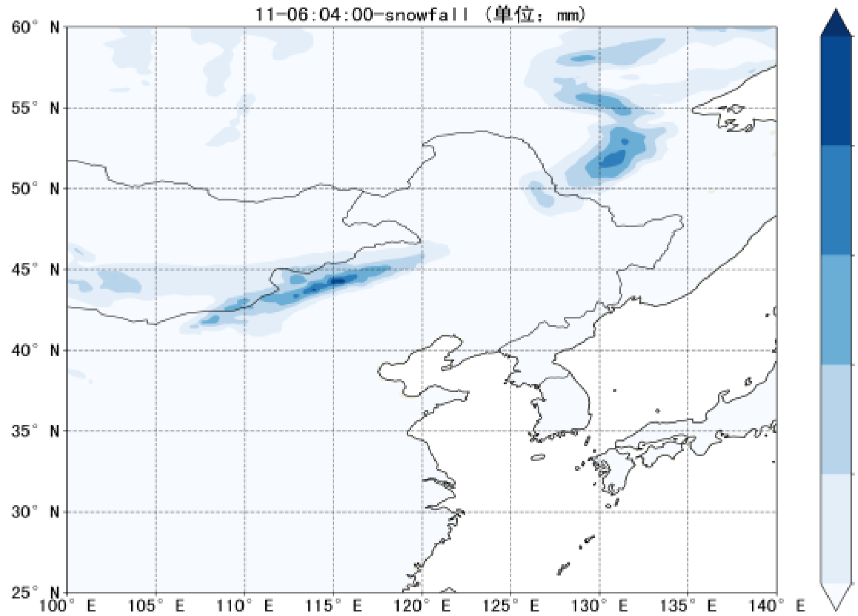


(d)

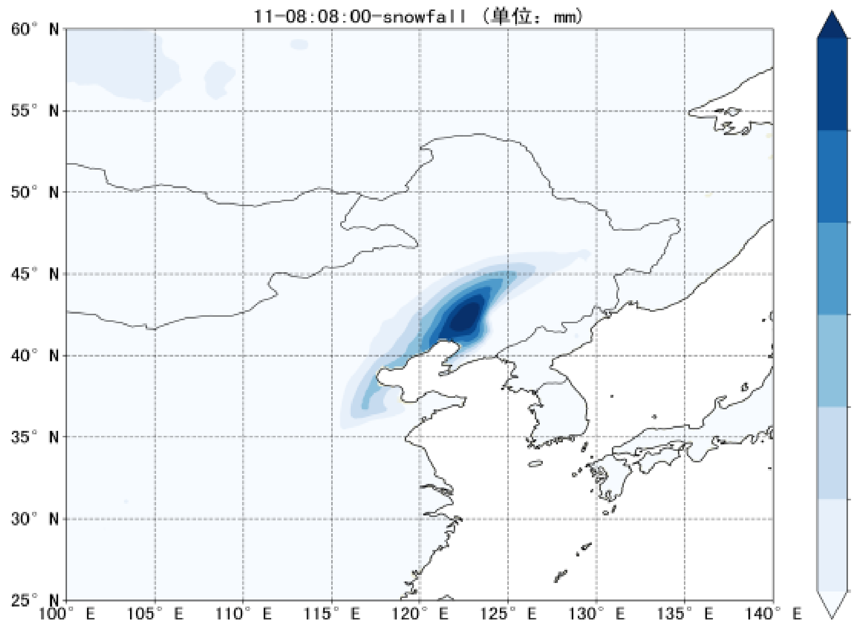
Figure 1. Distribution diagram of 500 hPa temperature field, height field and wind field in November 2021 (at 08 hours on (a): 04 day; (b): 07 at 0800 hours; (c): 08 at 0800 hours; (d): 0800 hours on 10 October; Temperature field: red isotherm and shadow area; High field: blue solid line; A wind vector.

wide impact range. Extreme snowfall occurred in southeast Inner Mongolia, central and western Liaoning, western Jilin and parts of Heilongjiang. Some areas fall more than 40 mm per hour (**Figure 2(b)**), snow depth reaches 10 to 20 cm, and local areas reach more than 30 to 40 cm, even since single station observation records. Primary and secondary schools in some areas were suspended, and Tongliao Airport, Changchun Airport, Dalian Airport, Taoxian Airport and Harbin Airport in Inner Mongolia and Northeast China were forced to close due to snow cover, and some expressways were severely regulated due to ice cover.

It is found that the peak snowfall time of Tongliao Airport in Inner Mongolia before November 9 was earlier than Shijiazhuang Zhengding Airport, Harbin Taiping Airport before Shenyang Taoxian Airport, Changchun Longjia Airport before Dalian Zhoushizi Airport, after November 9, Shenyang Tongliao Airport behind Shijiazhuang Zhengding Airport, Harjiazhuang Tao Airport. Before November 9, the peak snowfall time of the airport by north to west was earlier than that of the airport by east to south, and after November 9, the snowfall process of the airport by north to west was the same as that of the cold front under south to north, indicating that the snowfall process was affected by the cold front under south and then by the front cyclone. The evolution trend of three physical quantities, namely snow content, cloud column solid water content and cloud column liquid water content, is compared and analyzed in each airport. The hourly variation trend of solid water content (ice crystal, snow) extending from the surface of the earth to the top of the atmosphere at each airport corresponds well to the total snow content (**Figure 3** and **Figure 4**).



(a)



(b)

Figure 2. Hourly snowfall distribution map of "2021•11" ((a): 06:00 at 04th; (b): 08:00 at 08 th).

3. Analysis on the Cause of Snowfall

Snowfall is formed by the direct sublimation of water vapor in the atmosphere or the direct solidification of water droplets. Precipitation must not only have sufficient water vapor and cold ice crystal nuclei (near the surface temperature is about 0˚C), but also be formed under the condition of high and low altitude weather, energy conditions and physical quantity.

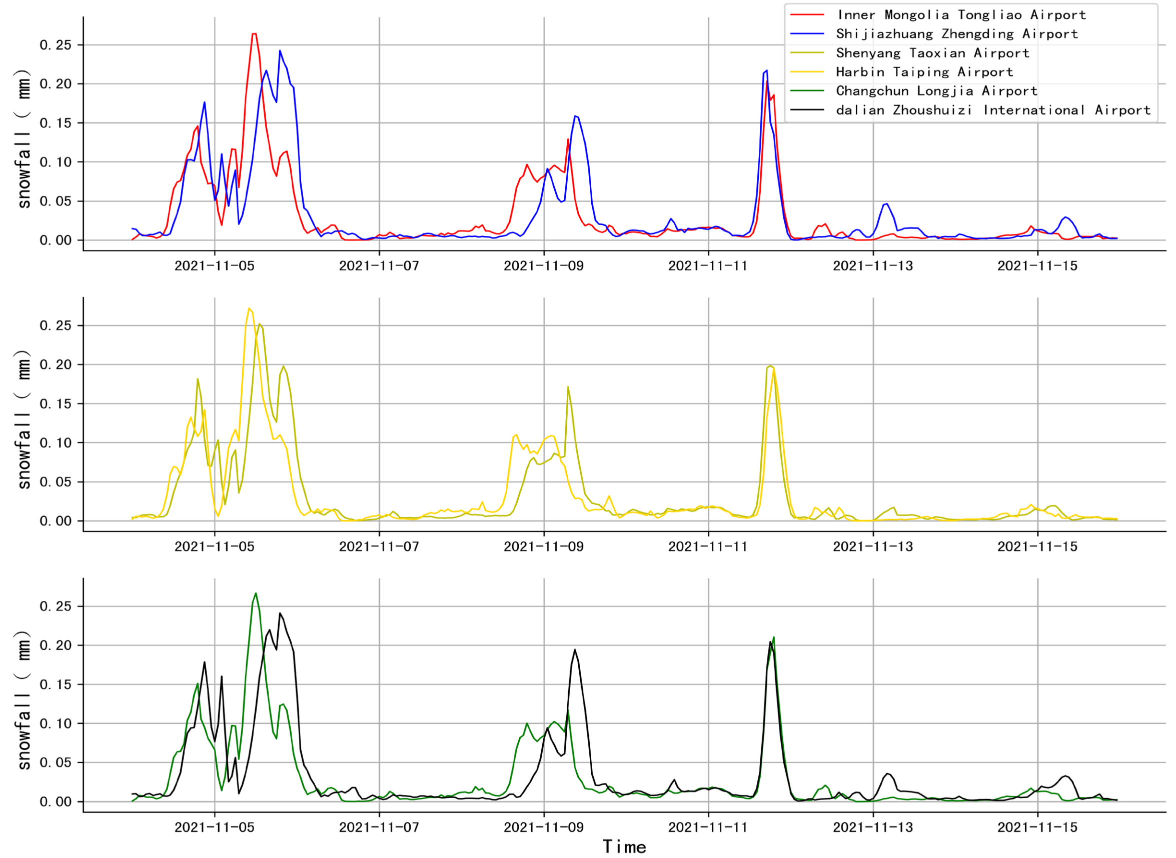


Figure 3. Hourly changes in snowfall at airports of "2021•11".

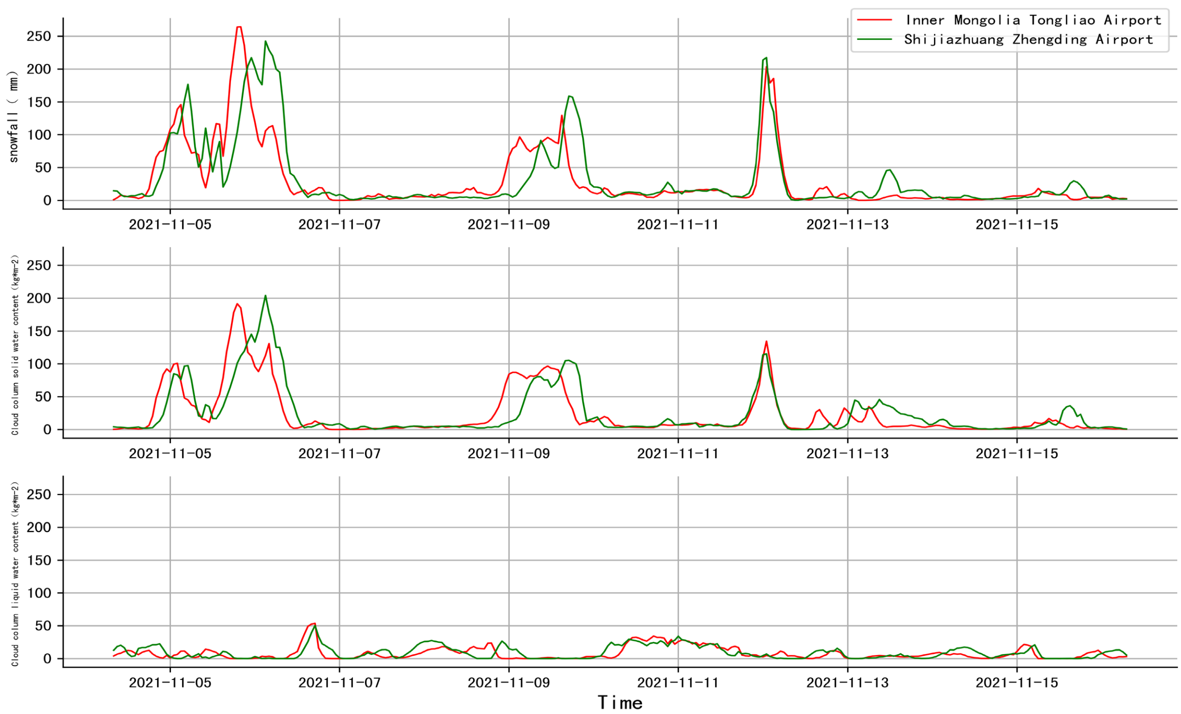


Figure 4. Change chart of snowfall, cloud column solid water content and cloud column liquid water content of "11/2021" at Tongliao Airport and Shijiazhuang Zhengding Airport in Inner Mongolia ((a): 06:00 at 04th; (b): 08:00 at 08 th).

3.1. Water Vapor Conditions

Through analysis, it is found that the relative humidity in most areas of Northeast China is more than 75% from November 4 to 12, but the physical quantity of water vapor such as relative humidity and specific humidity can only indicate that the water vapor condition in Northeast China can meet the conditions of snowfall, but the occurrence of strong snowfall requires constant water vapor supply. Vapor flux divergence (can be used to characterize the change of moisture content in a certain area. The water vapor flux divergence is positive for water vapor loss, and the water vapor flux divergence is negative for water vapor accumulation. Compared with the hourly snowfall and the water vapor flux dispersion during the snowfall, the water vapor flux dispersion in some areas is up to 11×10^{-6} g·cm^{-2}·hPa^{-1}·s^{-1} ($\nabla_p \cdot (Vq/g)$ **Figure 5(a)**). The center of strong snowfall appeared in the north of the positive center of water vapor flux divergence before the 9th day, and the center of strong snowfall appeared in the south of the positive center of water vapor flux divergence after the 9th day, and the larger the snowfall, the greater the water vapor flux divergence, the corresponding relationship between the position and intensity of strong snowfall (**Figure 2(b)**, **Figure 5(a)**).

Heavy rain or heavy snowfall requires constant water vapor input. Analysis of the hourly water vapor flux in the course of heavy snowfall shows that there is a long time strong water vapor transport process in the south of Northeast China and the sea, some of which are up to 18×10^{-6} g·cm^{-1}·s^{-1}. Comparing the snowfall with the water vapor flux, it is found that the larger the water vapor flux, the larger the snowfall (**Figure 2(b)** and **Figure 5(b)**).

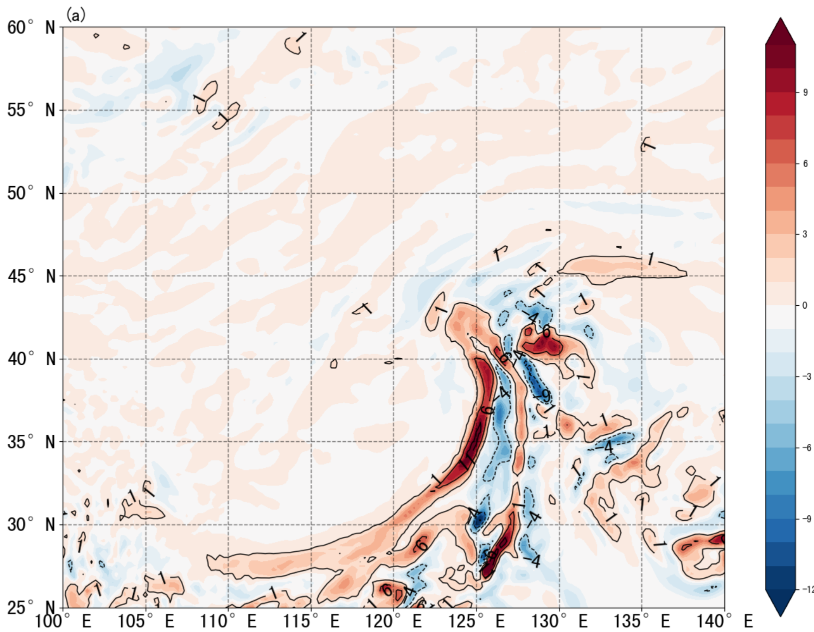
3.2. Dynamic Lifting Conditions

3.2.1. Ascending Motion

The positive and negative vertical velocity can directly indicate the direction of vertical motion, and the magnitude of the value can indicate the intensity of vertical ascending motion. In general, the higher the vertical velocity represents the stronger the ascending motion, the higher the lifting force produced. The hourly vertical velocity profile of some stations in Northeast China from May 05 to 12 shows that there is strong ascending motion at low altitude 850 hPa for a long time and obvious ascending and subsiding motion at 500 hPa. The maximum ascending period is 02:00 on 6, 09:00 on 8 and 20:00 on 10, and the period of heavy snow on the ground is almost corresponding to it. It is found that the center of heavy snow does not correspond to the closed center of positive velocity, but is at the beginning of closed center of positive velocity, and the gradient between positive velocity and negative velocity is larger, and the value of positive and negative center of vertical velocity is larger, the snowfall is larger, and vice versa.

3.2.2. "Suction Effect" of Divergence at Upper Level and Convergence at Lower Level

From November 05 to 12, 2021, the large area of northeast area of 100 hPa



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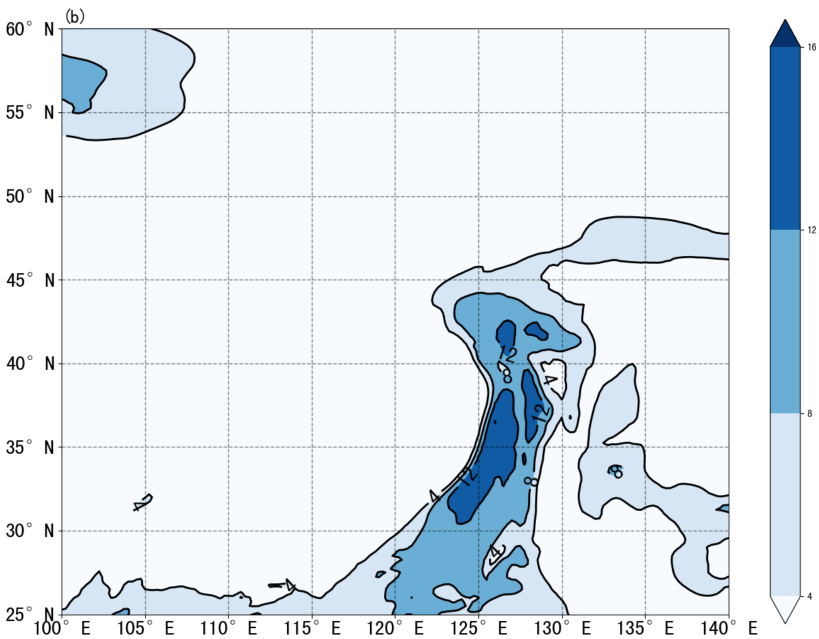


(b)

Figure 5. Spatial distribution diagram of water vapor condition at 08 hours on November 08, 2021 ((a): water vapor flux divergence in 10^6 g·cm^{-2}·hPa^{-1}·s^{-1}; (b): water vapor flux in 10^6 g·cm^{-1}·s^{-1}).

altitude map is obvious positive divergence area, while the low level 850 hPa is obvious negative divergence area, namely high-level divergence and low-level convergence. By 0800 hours on August 2008, the center of positive divergence was located in the southwest of Jilin Province, its head was located in the north of Heilongjiang Province (pictured below), and the corresponding 850 hPa was obviously negative divergence area. Afterwards, the altitude has been maintained positive divergence, low altitude negative divergence, especially in the day 8 - 10, high and low altitude divergence has obvious enhancement. At 8:00 on the 12th, the center of the positive divergence of the upper air moved north away from China, the positive divergence of the northeast area decreased gradually, and the 850 hPa divergence of the low air decreased correspondingly. From June 6 to 9, the Northeast region is in the situation of strong convergence of high and low, which is favorable for the convergence of water vapor and the occurrence of snow weather.

3.3. Energy Situation

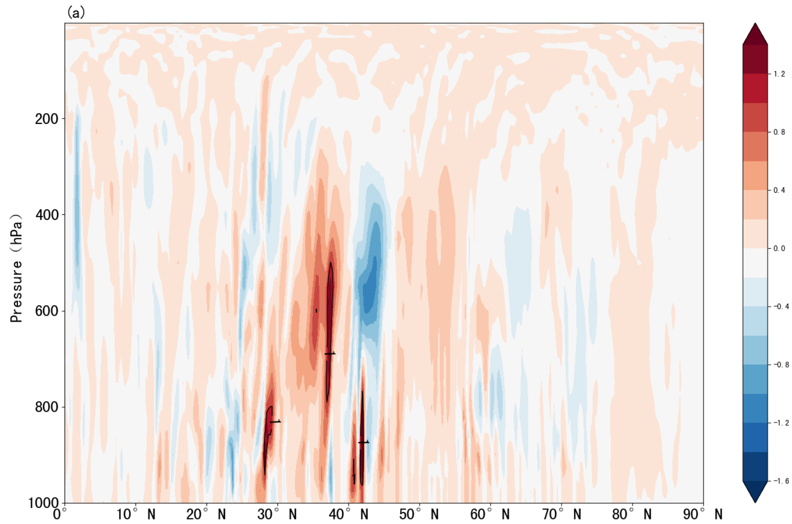
According to the 850 hPa temperature field, the 0˚C isotherm is in the 42˚N area, the 0˚C isotherm continuously moves south from 4 to 9 days, and a large amount of cold air descends south until the south edge reaches 22˚N. The isotherm line of 0˚C north after September 9, crossed the 42˚N area on December 12. During the snowfall process, most of the northeast area has been in the 850 hPa warm area, indicating that the energy in the early snowfall period and the snowfall period is more abundant. According to the temperature field at 850 hPa position, at 08:00 on 4th, the high energy tongue had reached the south of Jilin Province, and the position temperature was more than 20˚C. After that, with the pressure of the temperature front, the high energy tongue slowly retreats eastward and forms an energy front area in the eastern part of northeast (**Figure 6(a)**). The analysis of the temperature distribution chart at different height every hour shows that the energy in the northeast area has been continuously replenished, which is beneficial to the sustained heavy snowfall. But the supplementary energy gradually decreased after the 6th day, with time, the snow intensity decreased or even stopped when the additional energy was insufficient.

4. Effect of Heavy Snowfall on Flight

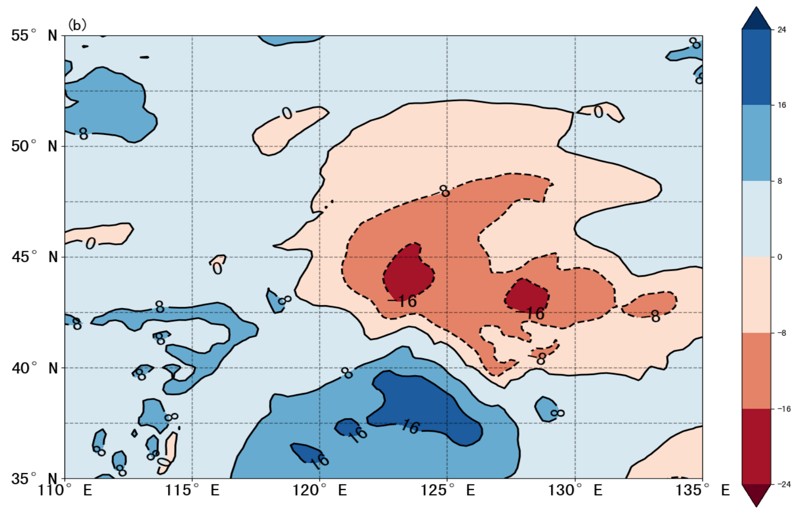
4.1. Threat to Take-Off and Landing Safety

During the heavy snowfall process, the relative humidity in the north and northeast of China is more than 75%, and the relative humidity in most areas of the northeast is more than 85% during November 4-12. Under high humidity conditions, low-level cloud with very low altitude and sometimes only a few tens of meters is easily formed, which causes low visibility and directly threatens the safety of take-off and landing.

The airport and surrounding areas are covered with snow after snowfall. Even if the runway snow can be removed, the snow covered on the runway and surrounding areas has strong emission effect on ultraviolet rays. The pilots do not pay attention to protecting the eyes during the flight. The ultraviolet rays can burn the eyes, and may cause conjunctivitis and keratitis in severe cases. Therefore, pilots should take certain precautions to prevent eyes from being burned by strong ultraviolet rays when flying in areas with snow on the lower surface.



(a)

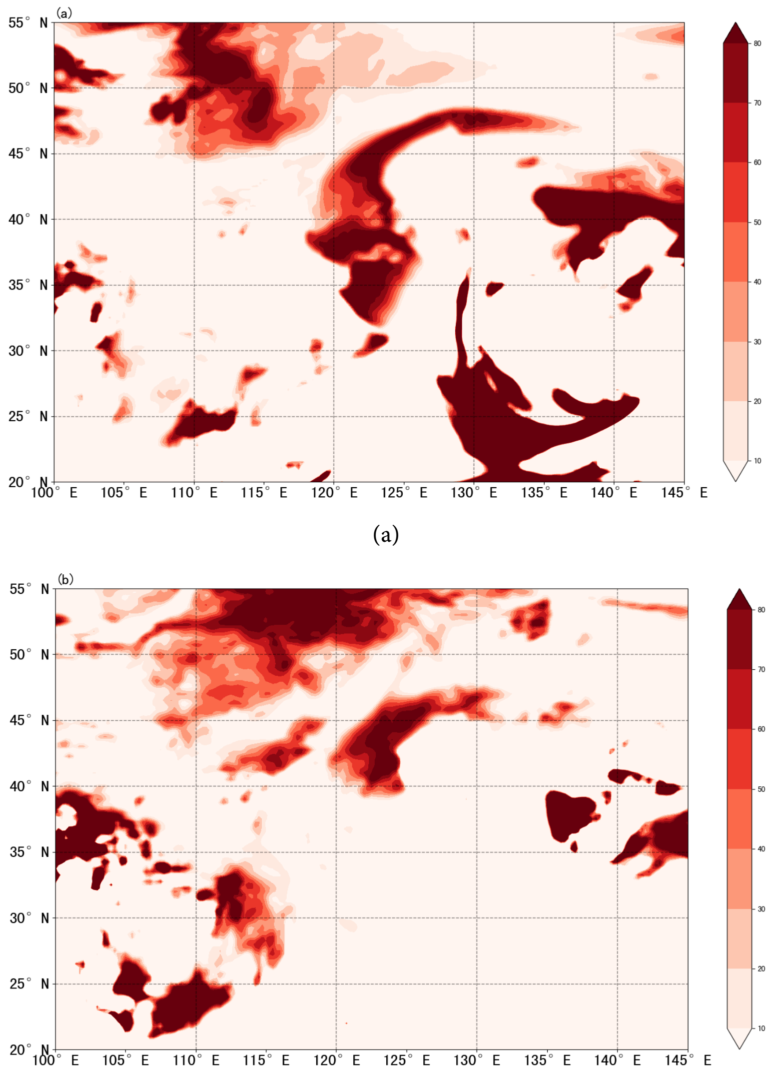


(b)

Figure 6. Dynamic lift at 08:00 November 8, 2021 ((a): vertical velocity profile in Pas^{-1}; (b): Horizontal dispersion in S^{-1}).

4.2. Aircraft Ice Accumulation

The visibility of heavy snowfall is low, while the atmospheric water vapor is abundant. Under certain temperature conditions (the surface temperature of the body is below 0˚C and the ambient temperature is above −30˚C), the super-cooled water droplets accumulate in some parts of the body surface to form ice deposition. Aircraft ice accumulation often occurs in aircraft wing, tail, propeller, airspeed tube, hydrostatic hole, antenna, windscreen, engine and inlet, etc. Once the ice accumulation occurs, the aerodynamic shape of aircraft will be changed, the aerodynamic characteristics and instrument communication of aircraft will be affected, and the maneuverability of aircraft will be abnormal and even the flight safety will be endangered. Abbreviation ICAO The ice accumulation index IC ($IC = [(RH - 50) \times 2] \times [t \times (t + 14)/(-49)]$) is commonly used to judge the intensity of aircraft ice accumulation, where RH is relative humidity and t is temperature (Chi et al., 2007). In the first half of IC exponential formula, relative humidity is used to represent the number and size of water droplets, and the second half of formula is used to fit the observed growth rate of water droplets. The exponent is positive, indicating the existence of potential ice accumulation area. The closer the ice accumulation index is 100, the more likely the ice accumulation is. Analysis of ice accumulation in aircraft at different altitudes during heavy snowfall of "11/2021" shows that because the south of northeast and moving areas provide continuous water vapor supply for northeast area, most of northeast area meets ice accumulation conditions for a long time, ice accumulation environment is mainly restricted by temperature. The IC index of November 5 - 12 finds that ice accumulation is always possible below 700 hPa altitude, and some areas are still strong ice accumulation environment (**Figure 7**),



(a)

(b)

Figure 7. Distribution of Ic Index at 08th on November 08, 2021 ((a): 850 hPa; (b): 975 hPa).

and the northeast area above 500 hPa is basically without ice accumulation environment. In a word, the key points of aircraft ice accumulation flight need to guard against areas below 500 hPa, avoid strong ice accumulation environment, correctly use anti-ice and de-icing devices, pay attention to aircraft ice accumulation near the ground during take-off and landing, and never take off or land with ice.

5. Conclusion

The heavy snowfall process in Northeast China was produced under the coordination of weather systems of different scales. Through the analysis of various physical fields, it is found that the heavy snowfall is caused by the abundant water vapor transport from south and southeast, the convergence rise of near ground layer, the "suction" effect of high level divergence, the air flow rise in vertical plane and a large amount of energy. The heavy snowfall influence on flight includes low visibility and ice accumulation.

1) 500 hPa northeast cold vortex, near surface cold front and front cyclone are the main influence systems of the snowfall weather. The southerly warm and humid flow prevailing in the front of northeast cold vortex provides sufficient water vapor and a great deal of energy for the snowfall. On November 4th, along with the cold front, a large amount of cold air descends south to form a "wedge", lifting relatively warm and humid air to a certain height, forming a "cold pad" near the ground. On November 7, the northeast area was affected and there was a clear northward process after 9 days. The warm and moist air in front of the front cyclone keeps climbing along the north of the front cyclone, which is favorable for the appearance of snow weather.

2) In the course of heavy snowfall, there is always a channel for water vapor transfer from south China, East China Sea and Bohai Sea to northeast China. The bigger the water vapor flux, the stronger the snowfall intensity; The positive value center of water vapor flux divergence has certain corresponding relationship with the location and intensity of strong snowfall center, which can be used as the index of snowfall forecast.

3) There is strong convergence of high and low level in the space structure near the heavy snowfall center, which is beneficial to the convergence and uplift of water vapor in the low level and is conducive to the occurrence of snowfall weather.

4) There is a good correspondence between the center of heavy snow and the vertical velocity, and the larger the vertical velocity gradient and the larger the vertical velocity center value, the larger the snow amount, and the smaller the vice versa.

5) The area south and east of Northeast China continuously replenishes energy to Northeast China, but the replenishment energy decreases with time, and the snowfall intensity decreases with the decrease of replenishment energy.

6) During the snowfall process, aircraft ice accumulation mainly occurred be-

low 700 hPa altitude, and above 500 hPa altitude there was basically no ice accumulation environment. Aircraft ice accumulation should be properly prevented and disposed of during the flight, avoiding strong ice environment.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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