WMO REGIONAL SPECIALIZED METEOROLOGICAL CENTER

FOR ATMOSPHERIC SAND AND DUST STORM FORECASTING

BEIJING

(RSMC-ASDF BEIJING)

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Contents

1. Forecasting Models in RSMC-ASDF BEIJING

Within the Regional Specialized Meteorological Center for Atmospheric Sand and Dust Storm Forecasting Beijing (RSMC-ASDF BEIJING), there are six operational SDS forecast models, including four global models from Japan, National Centers for Environmental Prediction (NCEP), European Centre for Medium-Range Weather Forecasts (ECMWF), Finland and two regional models from China and Korea. The following are brief introductions of SDS models developed by Asian countries (China, Japan and Korea).

Chinese Unified Atmospheric Chemistry Environment for Dust (CUACE/Dust), an integrated atmospheric chemistry modelling system applied to dust, was first established in 2002. It has been operationally run for dust forecast in China Meteorological Administration (CMA) since 2004 and for the World Meteorological Organization (WMO) Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) Asia Node-Regional Centre since 2007. CUACE/Dust has been designed as a unified chemistry module to be easily coupled with atmospheric models through a common interface. Its aerosol module utilizes a size-segregated multi-component algorithm for different types of aerosols including dust, sea salt, black and organic carbon, nitrate and sulphate. A detailed desert distribution with soil texture data base and dust particle-size distributions measurements from nine major deserts for China was adopted to the Model. One of the unique features of the CUACE/Dust is the implementation of a 3D-Var data assimilation system using both satellite and surface observations in near real-time to improve the initial conditions and hence the forecast results. A scoring system has been developed where observations from various sources concerning dust aerosol, i.e. surface observations of sand and dust storms and satellite retrieved Infrared Difference Dust Index (IDDI), are integrated into a Geographic Information System.

The former operational numerical dust forecast in Japan Meteorological Agency (JMA) was based on the Model of Aerosol Species in the Global Atmosphere (MASINGAR), which is directly coupled with the MRI/JMA98 AGCM. JMA has updated the operational dust forecast model (MASINGAR mk-2) to be based on the latest global climate model MRI-AGCM3 since November 2014. The model is coupled with the Scup coupler library. MASINGAR mk-2 treats five aerosol species: non-sea-salt sulphate, BC, OC, sea-salt, and mineral dust. The operational version of MASINGAR mk-2 calculates the emission flux of dust as a function of the friction velocity, soil moisture, soil type, snow cover and vegetation cover. Dust particles are logarithmically divided into 10 discrete size-bins from 0.1 to 10 μm in radius. Horizontal resolution of the MASINGAR mk-2 is set as TL 159 (about 120 km). JMA has a plan to upgrade horizontal resolution of the model to TL319 (about 60km) from

2016. JMA also has a plan to introduce data assimilation technique (LETKF) into MASINGAR mk-2 from 2019.

The Asian Dust Aerosol Model version3 (ADAM3) from Korea Meteorological Administration (KMA) was developed by incorporating the Asian dust emission algorithm into the Community Multiscale Air Quality model version 4.7.1. It is a Eulerian dust-transport model that includes specifications of dust source regions, delineated by a statistical analysis of WMO dust-reporting data and statistically derived dust emission conditions in sand, gobi, loess and mixed soil surfaces. The dust emission flux is assumed to be proportional to the fourth power of the friction velocity due to modifications of land use types in each source-grid region. It uses the suspended particle size distribution parameterized by the several log-normal distributions of the soil particle-size distribution in the source regions, based on the concept of minimally and fully dispersed particle-size distribution.

2. Products in RSMC-ASDF BEIJING

2.1 Model Products

At present, forecast and verification products of CUACE/Dust model from China, ADAM3 model from Korea, MASINGAR model from Japan, SILAM model from Finland，MACC model from ECMWF, and a dust forecast model from NCEP are provided through RSMC-ASDF BEIJING Web Portal (Table 1) (http://www.asdf-bj.net). It is estimated that daily data amount of SDS forecast product is about 4.5 GB during 2019-2020. And some SDS related observation products are also provided, such as PM_{10}, FY4A-IDDI, visibility and SDS weather phenomena (Table 2). The information of verification products of SDS models are shown in Table 3. Non-profit organizations could order SDS forecast products from RSMC-ASDF BEIJING by WMO WIS through Web Portal(www.asdf-bj.net).

Additionally, member countries could exchange observations and numerical forecast data with each other through data sharing FTP (ftp.nmc.cn). Historical forecast data could be requested via sds@cma.gov.cn.

Operational forecast products of 6 dust numerical forecast models and an ensemble forecast system were showed on a web portal maintained by RSMC-ASDF BEIJING. Forecast periods of CMA and FMI models were 7 and 5 days, respectively, and those of other models were 3 days. Forecast time intervals of all models were 3 hours. All forecast products were updated once a day during 06:30-08:15 (UTC).

The mandatory SDS products have been provided by The WMO RSMC-ASDF BEIJING according to the GDPFS manual since 2017, and forecasts cover the period from the starting forecast time(0000 UTC). Forecasts shall be disseminated through WIS and provided on a web portal in pictorial form not later than 12 hours after the starting forecast time. The following are mandatory products.

- Dust load (kg m^{-2})
- Dust concentration at the surface (μg m^{-3})
- Dust optical depth at 550 nm (-)
- 3-hour accumulated dry and wet deposition (kg m^{-2}).

In general, all the models and products ran stably during 2019-2020, but there were 1 integral overflow fault, 7 machine problems, 3 program faults, 3 upstream mode system faults, 11 data problems and 1 disk space fault. All above faults are eliminated in time within the specified time limit.

Table 1 Information of forecast products on the portal site

Parameter	**Area**	**Models**	**Resolution**	**Forecast range**	**Time steps**	**Frequency**
Dust load (kg m^{-2})	15-60 °N, 35-150 °E	CMA	0.5 °	7 days	3 hours	1 /day
		KMA	0.5 °	3 days		
		JMA	0.5 °	3 days		
		NCEP	1 °	3 days		
		ECMWF	0.5 °	3 days		
Dust concentration at the surface (μg m^{-3})	15-60 °N, 35-150 °E	CMA	0.5 °	7 days	3 hours	1 /day
		KMA	0.5 °	3 days		
		JMA	0.5 °	3 days		
		NCEP	1 °	3 days		
		ECMWF	0.5 °	3 days		
		FMI	0.5 °	5 days		
		Ensemble	0.5 °	3 days		
Dust optical depth at 550 (nm)	15-60 °N, 35-150 °E	CMA	0.5 °	7 days	3 hours	1 /day
		KMA	0.5 °	3 days		
		JMA	0.5 °	3 days		
		NCEP	1 °	3 days		
		ECMWF	0.5 °	3 days		
		FMI	0.5 °	5 days		
3-hour accumulated dry and wet deposition (kg m^{-2})	15-60 °N, 35-150 °E	CMA	0.5 °	7 days	3 hours	1 /day
		KMA	0.5 °	3 days		
		JMA	0.5 °	3 days		
		NCEP	1 °	3 days		
		ECMWF	0.5 °	3 days		

Table 2 Information of observation products on the portal site

Parameter	**Area**	**Frequency**
FY-4A IDDI	15-60 °N, 35-150 °E	24 /day
Visibility	15-60 °N, 35-150 °E	8 /day
Dusty weather phenomena	15-60 °N, 35-150 °E	8 /day

Table 3 Information of verification products on the portal site

Parameter	Area	Models	Forecast range	Time steps	Frequency
Forecasted surface-layer dust concentrations vs observed dusty weather phenomena	15-60 °N, 35-150 °E	CMA, KMA, JMA, NCEP, ECMWF, FMI, Ensemble	1 day	3 hours	1 /day

2.2 Service Products

According to the SDS weather impact intensity and area, once the SDS may bring serious harm to the affected areas according the forecast, the corresponding report will be issued timely. The following is the report and warning message for the downstream area of a sandstorm occurred from 14 to 16 March, 2021.

Mongolia, northern China and other places suffered from a wide range of SDS

Updated:Mar 15, 2021 16:37 PM

Source:China Meteorological News Press

On 14 March 2021, influenced by the strong Mongolian cyclone(Central sea level air pressure 980hPa) and its rear cold air, Mongolia had a large range of strong SDS, with the instantaneous wind force reaching 10-12 levels. On the night of the 14th, the cyclone moved to the South with the cyclone moving to the East, and a large range of SDS began to occur in the Midwest of Inner Mongolia China. As of this afternoon (15th), the eastern part of Xinjiang, Inner Mongolia, Gansu, Ningxia, Shanxi, Hebei, Heilongjiang had appeared In Jilin, Liaoning, Beijing, Tianjin and other places, sand or dust has been lifted successively. In Inner Mongolia, western Gansu, northern Ningxia, northern Shanxi, northern Hebei, Beijing Tianjin and other places, there are sandstorms or severe sandstorms. In Inner Mongolia, northwest, North China and Northeast China, there are 6-8 gales, with gusts of 10-11. Due to the influence of SDS, the minimum visibility of many places has decreased to less than 500 meters. Statistics show that the process is the strongest SDS process in China in recent 10 years. In many places, PM_{10} burst table appears. In Inner Mongolia, Gansu, Ningxia, northern Hebei and Beijing, PM_{10} peak concentration exceeds 5000 μg/m^3 The peak PM_{10} concentration in Beijing is over 9000 μ g/m^3.

It is expected that the SDS will gradually weaken on the 15th, but on the 16th, SDS will still occur in Northwest, North China, Huanghuai and Jianghuai areas affected by the SDS transport.(WMO RSMC-ASDF BEIJING)

Fig.1 Report and warning message of a sandstorm occurred from 14 to 16 March, 2021

2.3 Data Sharing

We have established an international data sharing ftp (ftp.nmc.cn) since early 2019. Asian regional forecast results of CMA, KMA, JMA, ECMWF, NCEP, and FMI’s dust forecast models and some site observations of PM_{10} concentration in Mongolia are shared among member countries every day. Member countries have all permissions for their own folders but only download permission for other countries’ folders. Its capacity will increase to 3 terabytes in 2021. In the future, we welcome more operational numerical dust forecast models and observation data to join this data sharing ftp.

2.4 Website Access

The RSMC-ASDF BEIJING conducts regular monitoring of website access. The results (Table 4) show the number of page views and unique visitor.

Table 4 Overview of web access in 2020

Season	**Page views**	**Unique visitor**
Jan. – Mar.	12055	5026
Apr. – Jun.	25079	11453
Jul. – Sep.	18233	8655
Oct. – Dec.	17198	11412
Total	72565	36546

3. Forecast Verification

In order to reduce the uncertainty of single numerical dust forecast model, a multi-model ensemble forecast system was build based on daily forecast results of all numerical models who joined RSMC-ASDF BEIJING, and its products are showed on Web-Portal (www.asdf-bj.net). Below is an example of SDS, taking place on 11-12 May, 2019.

Highly related to the influence of Mongolian cyclone and ground cold front, a severe SDS swept across western and northern China, leading to dusty weather in Inner Mongolia, Gansu, Ningxia, Shanxi, Shanxi, Hebei, Beijing and Tianjin on 11-12 May, 2019. Beijing Dust Operational Forecast Centre issued twice dust storm early warning information to the public, and provided warning advisory for other countries in Asian Node.

From the perspective of the SDS forecast of Beijing Dust Operational Forecast Centre, most of the numerical forecasts captured the spatiotemporal distribution of this process well. For example, at the most active moment of the process, the spatial distribution of high dust concentration forecasted by best ensemble matched well with that of observed dusty weather phenomenon reported in eastern Gansu, northern Ningxia, western Inner Mongolia and north Shaanxi (Figure 2). Figure 3 presented the time series of observed PM_{10} concentration and forecasted dust concentration by the ensemble in the city of Yinchuan located on the dust transport path. Results showed that the trends matched well associated with a relatively higher correlation coefficient of 0.79. And the forecasted occurrence and peak time of the case coincided with observation. In general, the forecasting effect of the Asian Node in 2019 is better, and the ensemble forecast can provide better results.

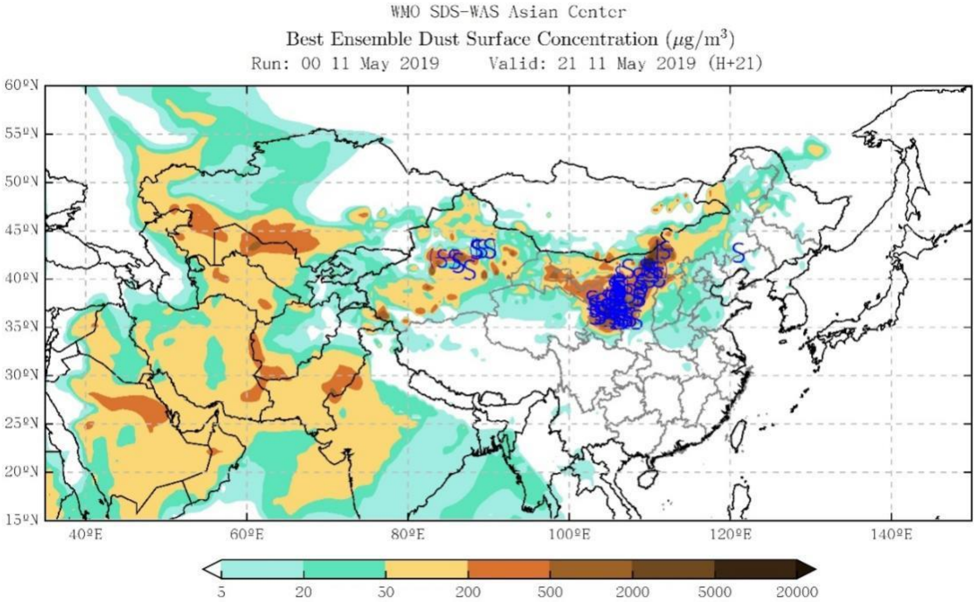


Fig. 2 Overlapping of observed dusty weather phenomenon observation and forecasted dust surface concentrations (μg m^{-3}) by best ensemble forecast at 21:00 (UTC) on May 11, 2019

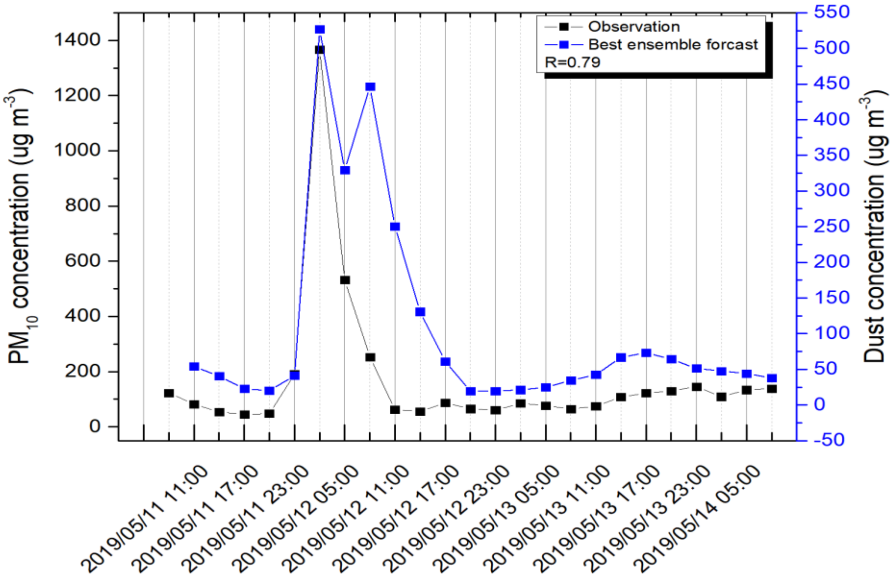
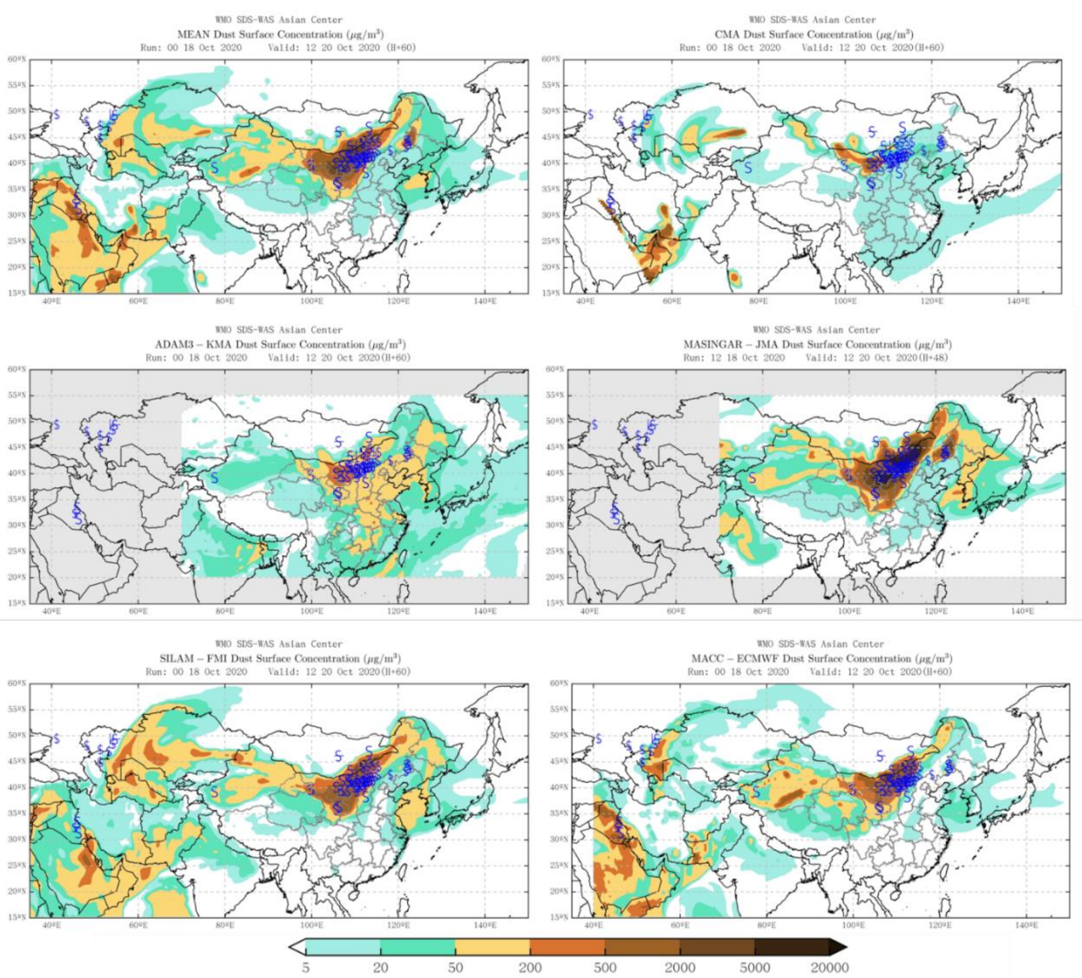


Fig. 3 Time series of observed PM_{10} concentration (μg m^{-3}) and forecasted dust concentration (μg m^{-3}) by the best ensemble in the city of Yinchuan (38.5 °N, 106.3 °E), Ningxia province China during May 11-14, 2019

In addition, numerical models and ensemble forecast have the ability to predict the strong dust process several days in advance. For example, the process with largest impact area in 2020 occurred from October 19 to 21. Numerical models in SDS-WAS Asian Node predicted this SDS process 1 to 2 days in advance (Figure 4). Mean ensemble predicted high dust concentrations in southeastern edge of Mongolia and central and western Inner Mongolia, Ningxia, northern Shaanxi, northern Shanxi and western Jilin provinces of China more than two days in advance, which matched well with most of locations with observed SDS weather phenomenon.



WMO SDS-WAS Asian Center
MEAN Dust Surface Concentration (μg/m³)
Run: 00 18 Oct 2020 Valid: 12 20 Oct 2020 (H+60)

WMO SDS-WAS Asian Center
CMA Dust Surface Concentration (μg/m³)
Run: 00 18 Oct 2020 Valid: 12 20 Oct 2020 (H+60)

WMO SDS-WAS Asian Center
ADAM3 – KMA Dust Surface Concentration (μg/m³)
Run: 00 18 Oct 2020 Valid: 12 20 Oct 2020 (H+60)

WMO SDS-WAS Asian Center
MASINGAR – JMA Dust Surface Concentration (μg/m³)
Run: 12 18 Oct 2020 Valid: 12 20 Oct 2020 (H+48)

WMO SDS-WAS Asian Center
SILAM – FMI Dust Surface Concentration (μg/m³)
Run: 00 18 Oct 2020 Valid: 12 20 Oct 2020 (H+60)

WMO SDS-WAS Asian Center
MACC – ECMWF Dust Surface Concentration (μg/m³)
Run: 00 18 Oct 2020 Valid: 12 20 Oct 2020 (H+60)

Fig. 4 Overlapping of observed dusty weather phenomenon and forecasted dust surface concentrations (μg m^{-3}) by each model and mean ensemble forecast at 12:00 (UTC) on Oct 20, 2020

4. Products Development

4.1 Development in SDS Satellite Monitoring

Based on the data of FY-3 and FY-4 satellites and dust monitoring products, a remote sensing dust monitoring and evaluation system of FY satellite was developed. It is a software system integrating satellite data acquisition, product display and statistical analysis, which can automatically process and manage data, and provide convenient and quick tools for various analysis and display.

The system includes the functions of basic data source acquisition, data projection and cutting, generation of dust color enhanced products, statistical analysis and data interaction. In the absence of human intervention, the system server automatically performs task operations. In the case of human-computer interaction, the client of the system displays the dust disaster products, and can make statistical analysis on the area and frequency of dust disaster.

The occurrence of dust and sand disasters in spring is frequent in China and its surrounding areas. The dust process on 15 May, 2019 was monitored and displayed continuously and completely by using the remote sensing dust disaster monitoring and evaluation system of FY satellite. Figure 5a was the dust color synthesis map of FY-4 with WMO satellite color synthesis scheme. It showed that a large range of dust pink appeared on the border between northern China and Mongolia. Based on the statistics of the dust monitoring products of FY-4, Figure 5b showed the occurrence frequency of dust in China in March 2020. According to the statistics, the dust process has affected 9 provinces and municipalities directly under the central government, with a disaster area of 353700 km^2.

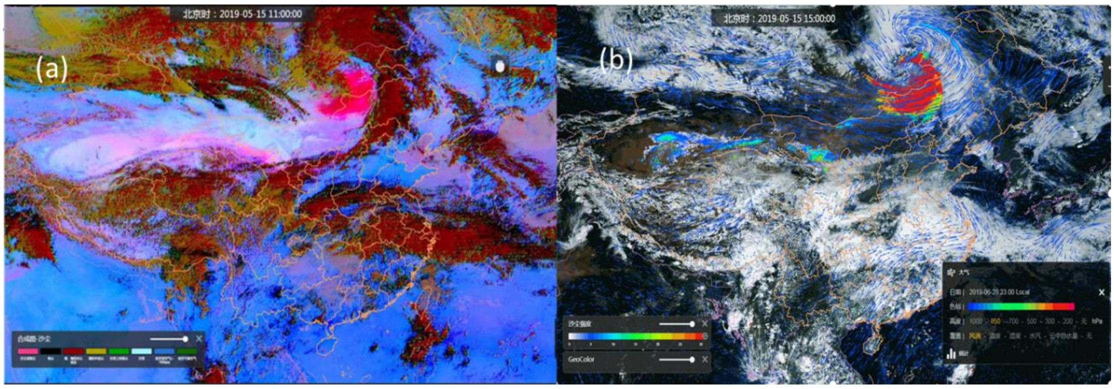


Fig. 5 FY-4 dust color composite map of WMO satellite color composite scheme (a); occurrence frequency of SDS (b)

4.2 Gridding SDS Surface Concentration

A preliminary gridding observed dust surface concentration dataset in China has been made based on surface site PM_{10} concentration observation, the ratio of dust to PM_{10} concentration and size distribution of dust aerosols using Cressman interpolation method.

4.3 Establishment of SDS Forecast Model Based on Seasonal Scale

A statistical multi-factor prediction model for spring SDS in northern China has been established. The model, which is taking into account of the influence of sea surface temperature (SST) and sea ice concentration (SIC) on spring atmospheric circulation over Eurasia and influence of rainfall on underlying conditions in dust-storm source region for northern China, is very skillful especially for North China and Northwest China. Besides, by using EOF iteration scheme, a dynamical downscaling model for monthly SDS frequency forecast in northern China has been set up also, which is based on the outputs either of the Atmospheric General Circulation Model of Beijing Climate Center (BCC_AGCM) or of the NCEP coupled forecast system model version 2 (CFSv2). The seasonal and S2S SDS models are both applied in the operational forecasting in the National Climate Center of China.

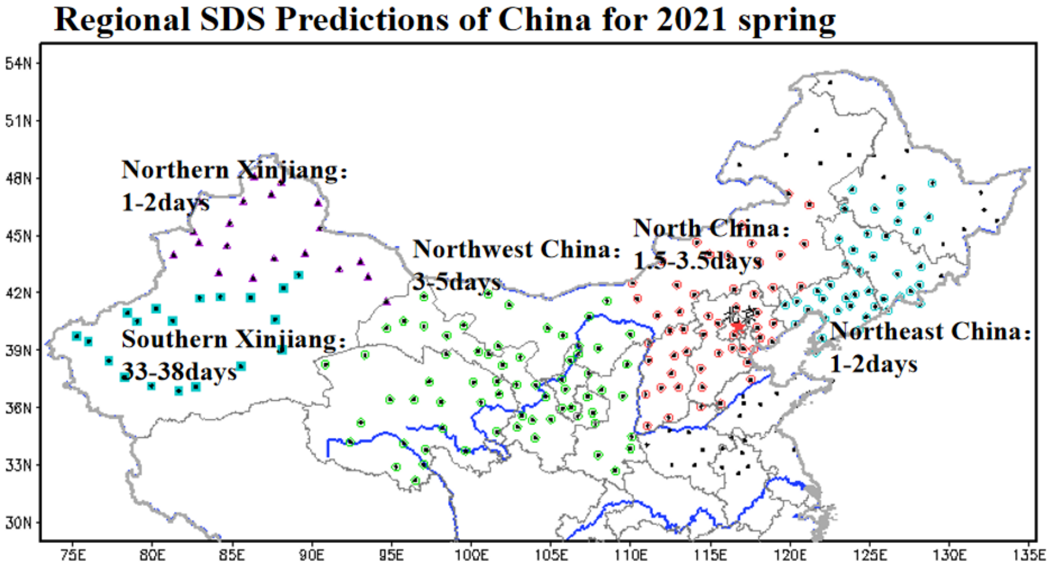


Fig. 6 Regional SDS predictions of China for 2021 spring

5. Development in SDS Models

5.1 Operational Improvements and Refine the Dust Sources in Asian Area of CUACE/Dust

Due to the improvement of the computing system in CMA, all the operational forecast systems should be moved to the new parallel computing system Pi-Sugon. CUACE/dust has also been moved to this new system with the new editing and compiling software. All the model codes have been check and recompiled to make it work smoothly (Fig. 7). Higher resolution of 0.25 ° meteorological IC/BC from global NWP model GRAPES have been adopted for CUACE/Dust with comparative tests to promise the accuracy. Meteorological errors in the model top layers which caused the abnormal abruption of the model run have also been corrected. Warm initialization for the sectional dust aerosol of CUACE/Dust has been established to promise the model forecast results continuity which makes the model forecast score improved obviously.

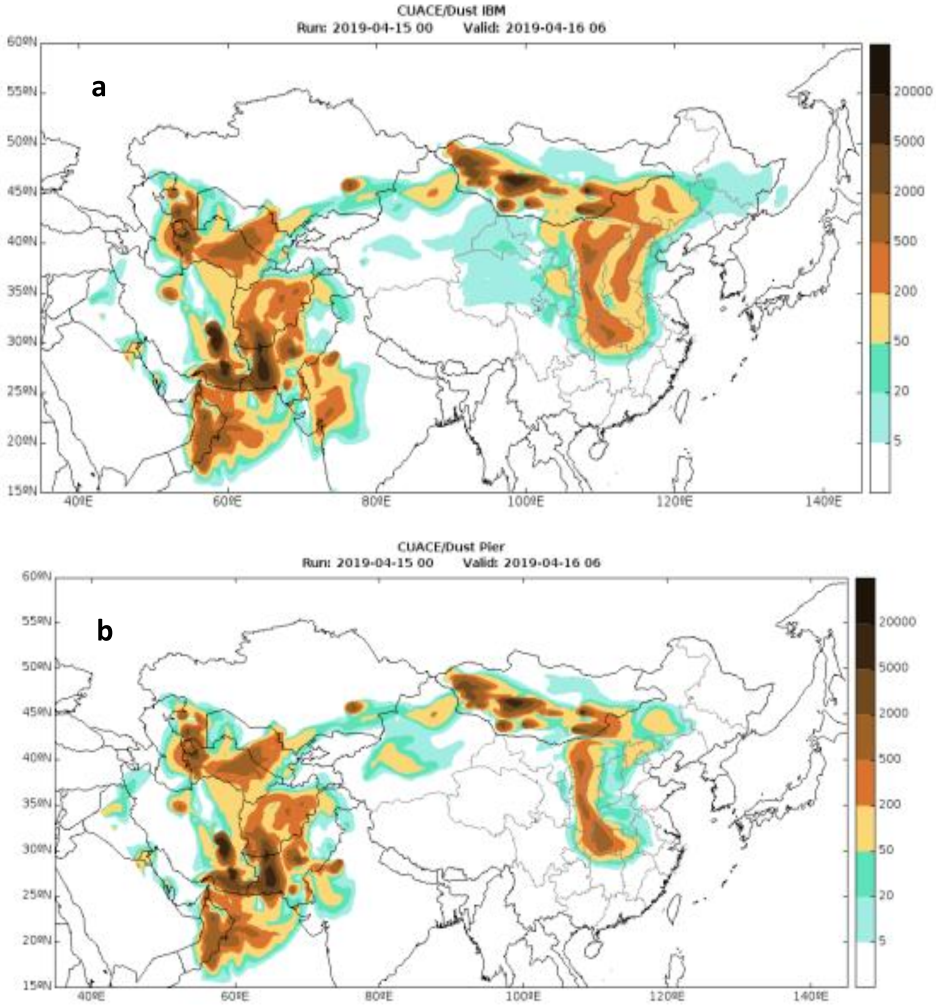


Fig. 7 Surface concentration forecast by CUACE/Dust at IBM (a); same as Fig.6 (a) but using Pi-Sugon (b)

The accuracy of dust emission is determined not only by the soil erosion physics schemes but also by the erosion database, including detailed soil (size distribution, texture, and composition) and land surface information (land use/land cover, roughness length, etc.). As the dust source region determines where dust is emitted to the air at a certain wind speed, major efforts have been made to improve the global dust source area distributions through satellite aerosol optical depth (AOD) data, updating land use/cover information of Asian source area information every five years by Institute of Geography, Chinese Academy of Sciences, and update 1-km global map on SDS sources (UNCCD report delivered at UNCCD COP14, Sep 2019, New Delhi, India). SDSs in Central and East Asia usually occur with the Siberian High, which can produce massive clouds that shade the SDS signals from satellite detection, so the satellite data are not sufficient to determine dust source areas in Mongolia and Central Asia, which are essential upstream dust source areas for SDS in Northeast Asia. Based on the observed meteorological SDS phenomena, especially the severe

SDSs and normal SDSs that are probably mainly formed directly by local emissions, the erodibility of the Asian source has been updated. SDS observations from meteorological stations from 2000 to 2017 were used to update the source areas that resulted in overestimated dust flux in Central Asia and underestimated dust flux in central and northern Mongolia in CUACE/Dust (Fig. 8).

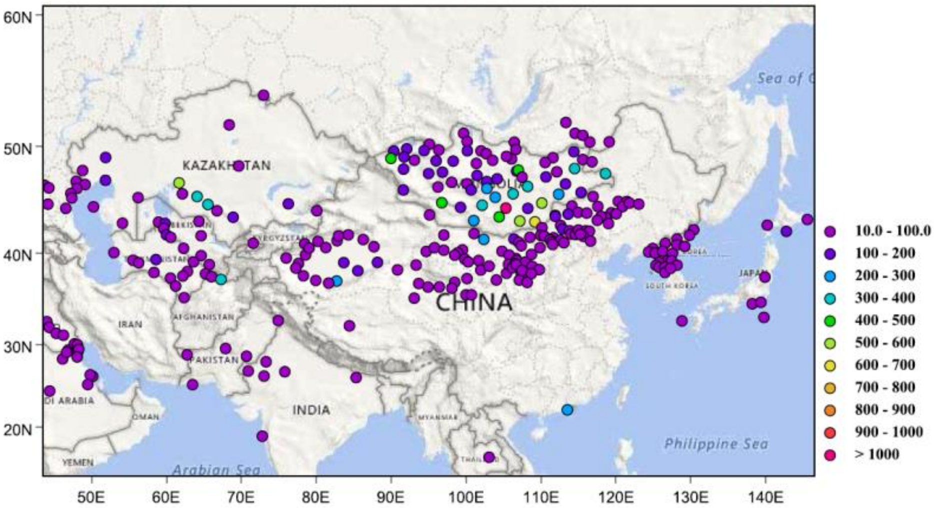


Fig. 8 Total number of observed dust events from 2000 to 2017 for severe sand and dust storms and sand and dust storms (Unit: days)

5.2 Improvement of the Asian Dust Aerosol Model Version3 (ADAM3) in 2020

The Asian Dust Aerosol Model version3 (ADAM3) was developed by incorporating the Asian dust emission algorithm into the Community Multiscale Air Quality model version 4.7.1, which is the chemical transport model developed at the United States Environmental Protection Agency. The meteorological fields used to drive ADAM3 simulations are obtained from the Global Data Assimilation Prediction System (GDAPS) which is the current global forecasting model used at KMA. Reduction index of Asian dust emission depending on precedent precipitation was applied to the dust emission algorithm in ADAM3 (ADAM3_RAIN) to improve over-estimation of Asian dust from ADAM3 in 2020. ADAM3_RAIN was considered accumulated precipitation ($PRain$) over the 3-hour period from 6 to 3 hours prior to the dust generations calculation. The reduction index PRf is formulated in terms of $PRain$ as

$$PRf = 0.1 \times e^{(-0.9\times PRain)}, if\ PRain > 0$$

where PRf varies between 0 and 1 and decreases as $PRain$ increases. To examine the impact of the PRf, we compared the simulation result of two ADAM3 and ADAM3-RAIN divided into precipitation (wet) and non-precipitation (dry) cases defined as the 24-h accumulated precipitation in GDAPS for dust emission regions in east Asia. The PM_{10} is evaluated by comparing the root mean square errors (RMSE) and mean bias errors (MBE) during the spring seasons in 2020 (Table 5). Compared with ADAM3, the error of ADAM3-RAIN run is consistently smaller, showing a maximum of 7.8 % improvement at dry cases over ADAM3. As ADAM3-RAIN can more realistically characterize dust emissions in the Asian dust source regions and PM_{10} mass concentration, the reduction index (*PRain*) applied to ADAM3 dust emission algorithm as of June 30, 2020.

Table 5. MBE and RMSE for the ADAM3 and ADAM3-RAIN runs. All represents total cases, whereas wet and dry denote precipitation and non-precipitation cases, respectively

	ADAM3		ADAM3-RAIN	
	MBE	RMSE	MBE	RMSE
All	10.2	90.2	3.8	86.4
Dry	16.0	73.7	9.6	68.3
Wet	2.8	64.2	-0.6	62.5

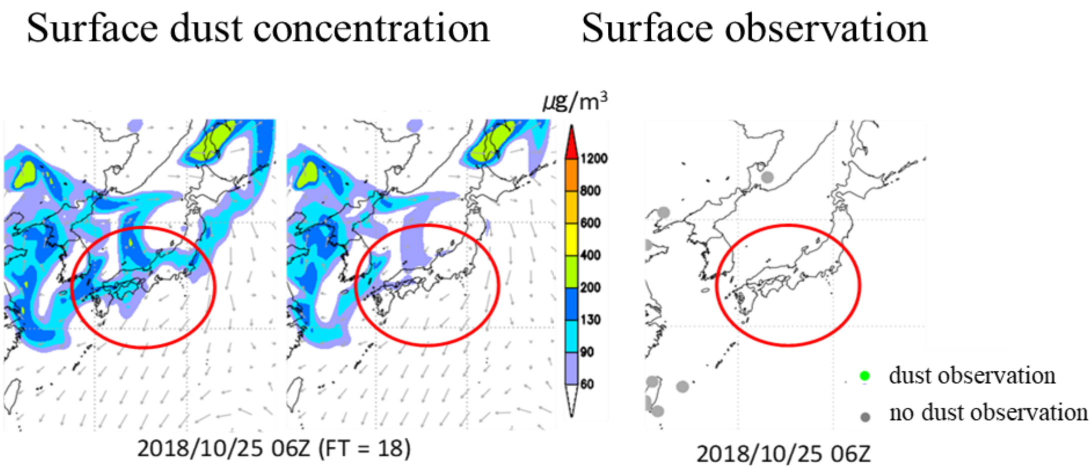
5.3 JMA Begins Operation of Himawari-8 Observation Data Assimilation System

The Japan Meteorological Agency (JMA) began operating a SDS prediction model in January 2004, and has been providing SDS forecasts and other SDS-related information through the JMA website and other media.

Observations by the Himawari-8 meteorological satellite, which began operations in July 2015, and Himawari-9, which is in standby operation, have enabled us to obtain wide-ranging and highly accurate aerosol observation data in the atmosphere with high frequency. The JMA, the Japan Aerospace Exploration Agency (JAXA), and Kyushu University had jointly developed a data assimilation system (2D-Var) to utilize these observation data in a SDS analysis and prediction model, and by introducing this system, started providing new SDS analysis and prediction information in January 2020.

Aerosol observation data from the meteorological satellites Himawari 8 and Himawari 9 are produced by operating the satellite aerosol product creation algorithm developed by JAXA at the JMA's Meteorological Satellite Center. In addition, the JMA's global aerosol model named MASINGAR mk-2 is capable of predicting the global distribution of aerosols, including SDS, through numerical simulations. The horizontal resolution of this model is 0.375 degree and the prediction period is 4 days. This model is a component of the Earth System Model of the Meteorological Research Institute (MRI), and is used by the JMA for forecasting SDS as well as for research on climate change. In the current model (data assimilated), as shown in the figure 9, the effect of the correction of predicted concentrations by data assimilation is evident, and there are no excessively large SDS areas, which are in good agreement with actual ground observations.

The MRI is doing research on the use of other satellite observation data (GCOM-C) for assimilation to further improve the SDS prediction model in the future.


Surface dust concentration

Surface observation

Fig. 9 Predicted surface dust concentration 18 hours ahead from the initial value (12:00 UTC on the 24th) by the former model (left), assimilation model (center) and the SYNOP report (right) at 06:00 (UTC) on October 25, 2018. In SYNOP report, gray circles indicate no dust observation, and green circles indicate dust observation.

6. International Activities

1) The 5th meeting of WMO SDS-WAS Steering Committee was held in Hangzhou, China, from 11 to 14 Nov. 2019. Zhang Xiaoye from CAMS, CMA was elected as new chair of the Steering Committee of SDS WAS.

2) The 7th Meeting of the Asian Regional Steering Group of WMO Sandstorm Early Warning Advisory and Assessment System (WMO SDS-WAS RSG for Asia) and the 3rd International Dust and Aerosol Workshop were held in Hangzhou China, from 11 to 14 November 2019.

Experts from participating countries reported on various fields of sand storm research and operational center development and discussed the current status, challenges, and future work of WMO SDS-WAS. The meeting agreed that member states need to strengthen cooperation in scientific research and business, and focus on data assimilation and sharing, dust monitoring, model performance evaluation, regional centers website construction, dust training and technical exchanges with other regional operational centers.

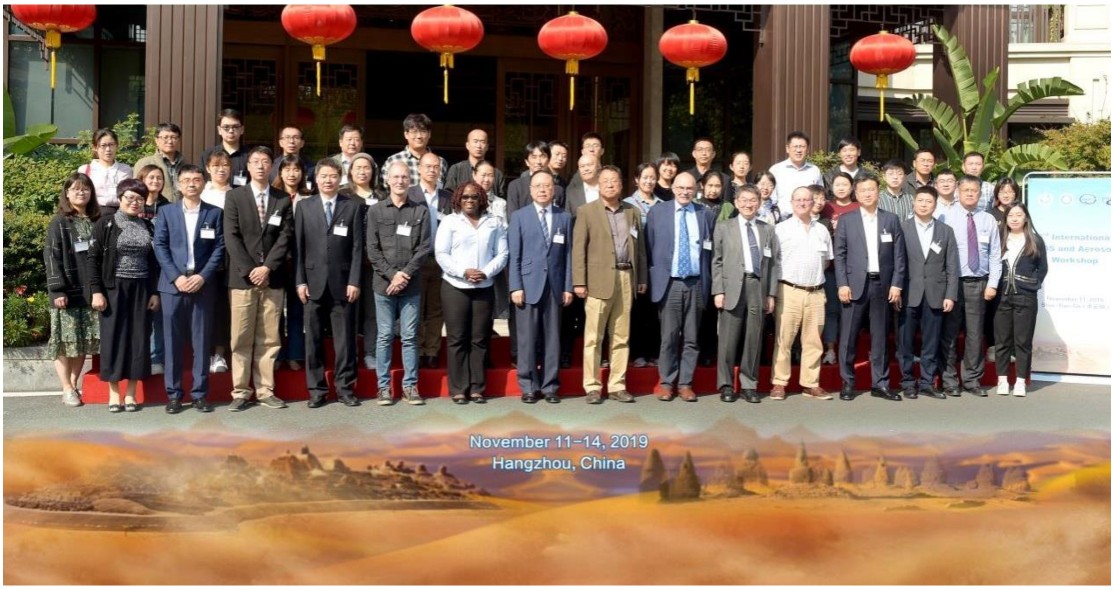
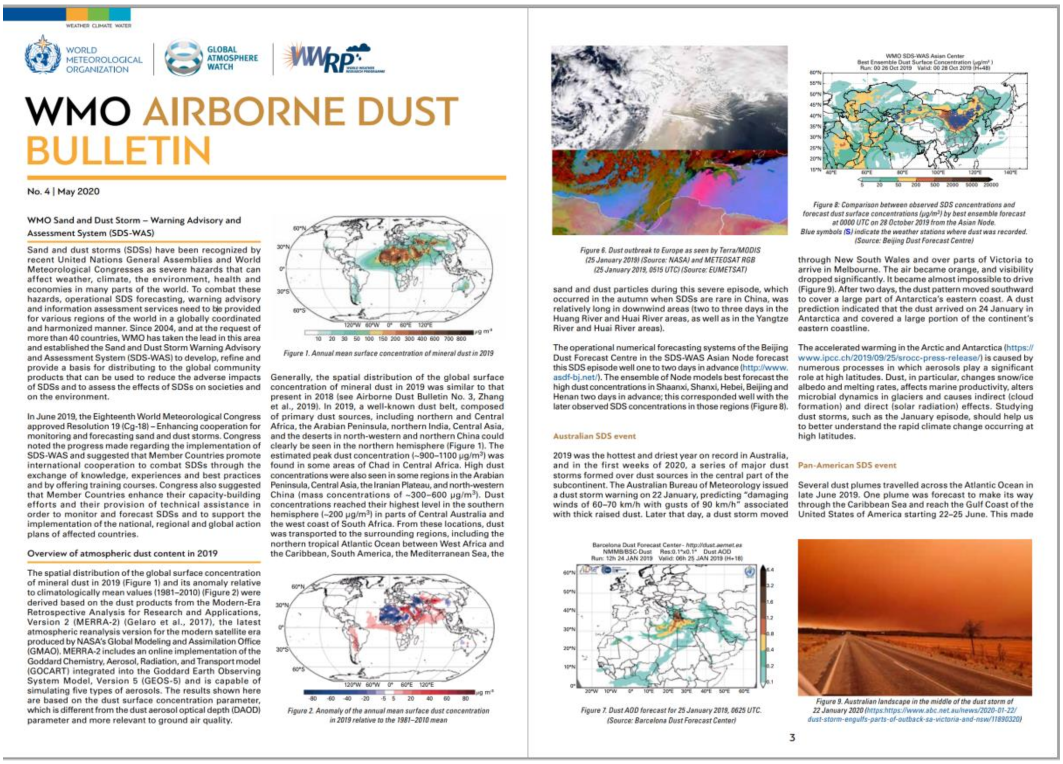


Fig. 10 The 3rd International Dust and Aerosol Workshop, The 7th Asian RSG of SDS-WAS and the 5th SDS-WAS Steering Committee Meeting held in Hangzhou China, from 11 to 14 November 2019

3) We contributed the overviews of SDS processes in Asia to the 2019 and 2020 WMO Airborne Dust Bulletin.



WMO AIRBORNE DUST BULLETIN

No. 4 | May 2020

WMO Sand and Dust Storm – Warning Advisory and Assessment System (SDS-WAS)

Sand and dust storms (SDSs) have been recognized by recent United Nations General Assemblies and World Meteorological Congresses as severe hazards that can affect weather, climate, the environment, health and economies in many parts of the world. To combat these hazards, operational SDS forecasting, warning advisory and information assessment services need to be provided for various regions of the world in a globally coordinated and harmonized manner. Since 2004, and at the request of more than 40 countries, WMO has taken the lead in this area and established the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) to develop, refine and provide a basis for distributing to the global community products that can be used to reduce the adverse impacts of SDSs and to assess the effects of SDSs on societies and on the environment.

In June 2019, the Eighteenth World Meteorological Congress approved Resolution 19 (Cg-18) – Enhancing cooperation for monitoring and forecasting sand and dust storms. Congress noted the progress made regarding the implementation of SDS-WAS and suggested that Member Countries promote international cooperation to combat SDSs through the exchange of knowledge, experiences and best practices and by offering training courses. Congress also suggested that Member Countries enhance their capacity-building efforts and their provision of technical assistance in order to monitor and forecast SDSs and to support the implementation of the national, regional and global action plans of affected countries.

Overview of atmospheric dust content in 2019

The spatial distribution of the global surface concentration of mineral dust in 2019 (Figure 1) and its anomaly relative to climatologically mean values (1981–2010) (Figure 2) were derived based on the dust products from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) (Gelaro et al., 2017), the latest atmospheric reanalysis version for the modern satellite era produced by NASA's Global Modeling and Assimilation Office (GMAO). MERRA-2 includes an online implementation of the Goddard Chemistry, Aerosol, Radiation, and Transport model (GOCART) integrated into the Goddard Earth Observing System Model, Version 5 (GEOS-5) and is capable of simulating five types of aerosols. The results shown here are based on the dust surface concentration parameter, which is different from the dust aerosol optical depth (DAOD) parameter and more relevant to ground air quality.

Figure 1. Annual mean surface concentration of mineral dust in 2019

Generally, the spatial distribution of the global surface concentration of mineral dust in 2019 was similar to that present in 2018 (see Airborne Dust Bulletin No. 3, Zhang et al., 2019). In 2019, a well-known dust belt, composed of primary dust sources, including northern and Central Africa, the Arabian Peninsula, northern India, Central Asia, and the deserts in north-western and northern China could clearly be seen in the northern hemisphere (Figure 1). The estimated peak dust concentration (~900–1100 µg/m^3) was found in some areas of Chad in Central Africa. High dust concentrations were also seen in some regions in the Arabian Peninsula, Central Asia, the Iranian Plateau, and north-western China (mass concentrations of ~300–600 µg/m^3). Dust concentrations reached their highest level in the southern hemisphere (~200 µg/m^3) in parts of Central Australia and the west coast of South Africa. From these locations, dust was transported to the surrounding regions, including the northern tropical Atlantic Ocean between West Africa and the Caribbean, South America, the Mediterranean Sea, the

Figure 2. Anomaly of the annual mean surface dust concentration in 2019 relative to the 1981–2010 mean

Figure 6. Dust outbreak to Europe as seen by Terra/MODIS (25 January 2019) (Source: NASA) and METEOSAT RGB (25 January 2019, 0515 UTC) (Source: EUMETSAT)

sand and dust particles during this severe episode, which occurred in the autumn when SDSs are rare in China, was relatively long in downwind areas (two to three days in the Huang River and Huai River areas, as well as in the Yangtze River and Huai River areas).

The operational numerical forecasting systems of the Beijing Dust Forecast Centre in the SDS-WAS Asian Node forecast this SDS episode well one to two days in advance (http://www.asdf-bj.net/). The ensemble of Node models best forecast the high dust concentrations in Shaanxi, Shanxi, Hebei, Beijing and Henan two days in advance; this corresponded well with the later observed SDS concentrations in those regions (Figure 8).

Australian SDS event

2019 was the hottest and driest year on record in Australia, and in the first weeks of 2020, a series of major dust storms formed over dust sources in the central part of the subcontinent. The Australian Bureau of Meteorology issued a dust storm warning on 22 January, predicting "damaging winds of 60–70 km/h with gusts of 90 km/h" associated with thick raised dust. Later that day, a dust storm moved

Figure 7. Dust AOD forecast for 25 January 2019, 0625 UTC. (Source: Barcelona Dust Forecast Center)

Figure 8: Comparison between observed SDS concentrations and forecast dust surface concentrations (µg/m^3) by best ensemble forecast at 0000 UTC on 28 October 2019 from the Asian Node. Blue symbols (S) indicate the weather stations where dust was recorded. (Source: Beijing Dust Forecast Centre)

through New South Wales and over parts of Victoria to arrive in Melbourne. The air became orange, and visibility dropped significantly. It became almost impossible to drive (Figure 9). After two days, the dust pattern moved southward to cover a large part of Antarctica's eastern coast. A dust prediction indicated that the dust arrived on 24 January in Antarctica and covered a large portion of the continent's eastern coastline.

The accelerated warming in the Arctic and Antarctica (https://www.ipcc.ch/2019/09/25/srocc-press-release/) is caused by numerous processes in which aerosols play a significant role at high latitudes. Dust, in particular, changes snow/ice albedo and melting rates, affects marine productivity, alters microbial dynamics in glaciers and causes indirect (cloud formation) and direct (solar radiation) effects. Studying dust storms, such as the January episode, should help us to better understand the rapid climate change occurring at high latitudes.

Pan-American SDS event

Several dust plumes travelled across the Atlantic Ocean in late June 2019. One plume was forecast to make its way through the Caribbean Sea and reach the Gulf Coast of the United States of America starting 22–25 June. This made

Figure 9. Australian landscape in the middle of the dust storm of 22 January 2020 (https:https://www.abc.net.au/news/2020-01-22/dust-storm-engulfs-parts-of-outback-sa-victoria-and-nsw/11890320)

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Fig.11 Pages of 2019 WMO Airborne Dust Bulletin

7. Publications

1. Zhou C. H., Zhang X. C., Zhang J. et al., 2021. Representations of dynamics size distributions of mineral dust over East Asia by a regional sand and dust storm model, Atmospheric Research,

Volume 250, 105403, ISSN 0169-8095, https://doi.org/10.1016/j.atmosres. 2020. 105403.

2. Zhou C. H., Gui H. L., Hu J. et al., 2019. Detection of new dust sources in central/East Asia and their impact on simulations of a severe sand and dust storm. Journal of Geophysical Research: Atmospheres, 124. https://doi.org/10.1029/ 2019JD030753.

3. Jiang Q., Gui H. L., Zhang T. H. et al., 2020. Estimation of gridding surface atmospheric particle matter concentration in China based on FY-4A satellite observation. Meteorological Monthly. 46(10), 1297-1309.

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Appendix

Overview of Asian SDS Events during 2019-2020

Summary of all dust events occurred in East Asia during 2019-2020 was showed in Table A1. In 2019, 15 dust events occurred in East Asia with 9 Blowing and Floating Dust (BFD) processes, 5 SDS processes and a sever SDS process, which was higher than the historical average. Compared with 2019, only 10 dust events occurred in East Asia during 2020. Among them, there were 7 BFD processes, 2 SDS process, and a sever SDS process.

The most influential event was the BFD process occurred from October 27 to 30, 2019, affecting most parts of northern China. The most intensive event was the sever SDS process occurred from March 8 to 10 in 2020. Blowing sand and floating dust occurred in the northwest China, Southern Mongolia, Sand and dust storms occurred in parts of northwest China and parts of Southern Mongolia, Severe sandstorms occurred locally. What's more, some large-scale dust weather processes occurred in autumn in these two years., which was relatively rare in previous years.

Table A1 Summary of dust events occurred in East Asia during 2019-2020

No.	Time Period	Grade	Affected Area
201901	19-24 Mar	Sever SDS[1]	BFD occurred in northwest China, central and Southern Mongolia. SDS occurred locally in parts of northwest China, parts of central and Southern Mongolia, parts of Southern north Korea.
201902	4-5 Apr	BFD[2]	BFD occurred in parts of northwest China, the Mideast of Inner Mongolia, northeast China, north China, Huanghuai plain, the Mideast of Mongolia, SDS occurred in the mideast part of Mongolia, the middle part of north Korea.
201903	16 Apr	BFD	BFD occurred in the west of northeast China, the Middle and southern of Mongolia, SDS occurred in the middle and southern parts of the Mongolia.
201904	17 Apr	BFD	BFD occurred in central and Eastern Inner Mongolia, the west of northeast China and eastern Mongolia, SDS occurred in the eastern part of Mongolia, the middle part of north Korea.

201905	20 Apr	BFD	BFD occurred in central and Eastern Inner Mongolia, the west of northeast China, north China, central and Southern Mongolia; SDS occurred locally in northwest China, parts of central and Southern Mongolia.
201906	26-28 Apr	SDS	BFD occurred in northwest China, the western of Mongolia, SDS occurred in parts of northwest China, the western part of Mongolia, Severe SDS occurred locally.
201907	4-5 May	BFD	BFD occurred in northwest China; SDS occurred in parts of northwest China.
201908	11-12 May	SDS	BFD occurred in northwest China, north China, Southern Mongolia and Southern Japan; SDS occurred in parts of northwest China and parts of Southern Mongolia.
201909	14-16 May	SDS	BFD occurred in northwest China, the west of northeast China, southeast Mongolia, SDS occurred in parts of northwest China and parts of southeast Mongolia.
201910	18-19 May	BFD	BFD occurred in northwest China, parts of north China, and southern Mongolia, SDS occurred in parts of Southern Mongolia.
201911	24-26 May	BFD	BFD occurred in northwest Cand southwest Mongolia, SDS occurred locally in parts of northwest China, parts of Southwest Mongolia and eastern north Korea.
201912	26-27 Jul	SDS	BFD occurred in the West of northwest China, SDS occurred locally in parts of northwest China.
201913	17-18 Aug	SDS	BFD occurred in northwest China, SDS occurred in parts of northwest China.
201914	27-30 Oct	BFD	BFD occurred in northwest China, north China, Huanghuai Plain.
201915	17-18 Nov	BFD	BFD occurred in northwest China, north China, parts of northeast China and Southern south Korea.
202001	13-15 Feb	SDS	BFD occurred in northwest China and Southern Mongolia, SDS occurred in parts of northwest China and parts of Southern Mongolia, Severe SDS occurred locally.
202002	8-10 Mar	Sever SDS	BFD occurred in the northwest China, Southern Mongolia, SDS occurred in parts of northwest China and parts of Southern Mongolia, Severe SDS occurred locally.
202003	12 Mar	BFD	BFD occurred in parts of northwest China.

202004	18 Mar	BFD	BFD occurred in northwest China, north China, Huanghuai plain, central and Southern Mongolia, SDS occurred in parts of Southern Mongolia.
202005	25-26 Mar	BFD	BFD occurred in northwest China, the west of northeast China, central and Southern Mongolia, SDS occurred in parts of northwest China, parts of central and Southern Mongolia, Severe SDS occurred locally.
202006	10-11 Apr	SDS	BFD occurred in northwest China, SDS occurred in parts of northwest China, Severe SDS occurred locally.
202007	10-11 May	BFD	BFD occurred in the southeast of Inner Mongolia, northeast China, and the Southeastern Mongolia, SDS occurred in parts of Southern Mongolia.
202008	11-12 May	BFD	BFD occurred in the middle of Inner Mongolia, north China, Huanghuai Plain, and the Southeastern Mongolia, SDS occurred in parts of Southern Mongolia.
202009	1 Jun	BFD	BFD occurred in parts of northwest china, the west of north China, Huanghuai Plain and the Southwestern Mongolia, SDS occurred in parts of northwest China, and in parts of Southern Mongolia.
202010	20-21 Oct	BFD	BFD occurred in northwest China, north China, northeast China and Huanghuai Plain.

[1] SDS, Sand and Dust Strom process

[2] BFD, Blowing and Floating Dust process