CHARACTERISTICS OF YELLOW SEA FOG UNDER VARYING AEROSOL CONDITIONS

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ABSTRACT

Sea fog usually refers to a fog that occurs under the influence of the ocean, and the Yellow Sea is a region where sea fog regularly occurs. Fog occurrence and structure is impacted by aerosol concentration in the air where the fog forms. Along with industrial development, air pollution, and thus aerosol concentration has increased and become a serious environmental problem in Northeastern China. These higher pollution levels are confirmed by various satellite remote sensing instruments including Moderate Resolution Imaging Spectroradiometer (MODIS) aboard on the Aqua satellite, Ozone Monitoring Instrument (OMI) aboard on the EOS-Aura satellite, and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite which observe aerosol, ozone and cloud properties. These observations show a clear influence of aerosol loading over the Yellow Sea region which can have an impact on the regional sea fog.

High-resolution data sets from MODIS Aqua L2 are used to investigate the relationships between cloud properties, aerosol (AOD, aerosol optical depth), and SST features. The result of the bi-variate comparison method shows that for most of the cases, larger values of COT (Clout Optical Thickness) are related to both smaller ER (Droplet Effective Radius) and higher CTH (Cloud Top Height). However, for the cases where fog is relatively thinner with many zero values in CTH, the larger COT is related to both smaller ER and CTH. For the fog cases where AOD is dominated by smoke (e.g. confirmed fire activities in the East China Plain) the Semi Direct Effect/Cloud Burning of Soot likely plays a role in determining fog structure. The large amount of absorbing aerosol caused by fires can absorb sunlight and increasing the temperature of the air near surface, which can burn away clouds and result in a relationship where smaller ER corresponds with thinner fog and smaller COT values.
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CHAPTER 1
INTRODUCTION

1.1 Fog

Fog is one of the weather phenomena that we experience in our daily lives. The American Meteorology Society (https://glossary.ametsoc.org/wiki/Fog) shows that: “fog is defined as the water droplets suspended in the atmosphere near the surface of the earth that can affect the visibility. According to the international definition, fog can reduce visibility below 1 km (0.62 miles). The only difference between fog and a cloud is that the base of fog is at the earth’s surface while clouds are above the surface.” The American Meteorology Society also shows that the main mechanism for fog is such that: “Fogs originate when the temperature and dewpoint of the air become the same (or nearly the same). It may occur through cooling of the air to a little beyond its dewpoint (producing advection fog, radiation fog or upslope fog), or by adding moisture and elevating the dewpoint (producing the steam fog or frontal fog). Fog seldom forms when the dewpoint spread is greater than 4 °F.” According to the American Meteorology Society, the difference between fog, haze, and mist is that: “The fog can be easily distinguished from haze by its higher relative humidity (near 100%, having physiologically appreciable dampness) and gray color. Another thing is that haze does not contain activated droplets larger than the critical size according the Köhler theory. While mist may be considered an intermediate between fog and haze, the particles of mist are smaller in size, it has lower relative humidity than fog, and does not obstruct visibility to the same extent.”

1.2 Sea Fog

Sea fog usually refers to fog that occurs under the influence of the ocean (B. Wang, 1985). It is a global phenomenon that occurs in coastal regions and over the open ocean, especially in the Northwest Atlantic and Pacific regions (Koračin et al.
With the expansion and development of air, land, and sea traffic, sea fog has the potential to have a significant impact on human activities. It can influence marine transportation, harbor activities, coastal road traffic, and other maritime activities (Koračin et al. 2017). Economic losses caused by low visibility of sea fog can be comparable to those caused by other weather such as tornadoes, or hurricanes (Gultepe et al. 2007).

While there are many negative impacts resulting from fog events, there are many positive impacts as well. Sea fog events have a cleaning effect on the environment, for example, the air quality can be improved after the occurrence of fog via the process of wet deposition (Koračin et al. 2017).

However, the harmful consequences of sea fog cannot be ignored. According to the Qingdao Maritime Safety Administration, nearly 50% of ship collisions or stranding accidents were related to sea fog between 2000 and 2003 (Zhang & Bao, 2008). To reduce economic losses incurred by coastal cities due to sea fog events, it is of great importance to improve forecast accuracy (Gao et al. 2018; Wang et al. 2014). Despite the importance of forecasting sea fog events, there are many factors that make accurate forecasts difficult to achieve (Bergot & Guedalia, 1994; Gao et al. 2007; Pagowski et al. 2004; Y. Wang et al. 2014). For example, the sensitivity tests delivered by the MM5 (Fifth-generation Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model) show that the modeling results are significantly influenced by different planetary boundary layer schemes and SST, which makes it challenging to simulate and predict sea fog (Gao et al. 2007).

### 1.2.1 Yellow Sea Fog

Sea fog thickness can reach 1 km in depth along the China coast and can extend 100 – 200 km offshore (Koračin et al. 2017). The most frequent fog occurrence area is on the coast of the Shandong Peninsula (Koračin et al. 2017). The average annual number of fog days reaches 83 days in Chengshantou (CST) station (Yang et al. 2019), which is located in the easternmost region of the Shandong Peninsula.
(Figure 5). According to observations, the most frequent fog occurrence area is in the northeastern part of Yellow Sea from June to August, and along the entire coast from December to February. This difference of location over time is due to a combination of seasonal fluctuations of the Kuroshio Current, which can transport warm water along the eastern coast of China. During March to May and June to August, weak synoptic lows move east and northeast, which brings warm, moist air over the colder water and increase the fog and mist occurrences during these days (Koračin et al. 2017).

Previous studies show that Yellow Sea fog is characterized as advection fog, which refers to the type of fog that is generated under the condition when air moves over a surface with different temperature (Yang et al. 2019; Koračin et al. 2014; Figure 1). Specifically, fog generated when warm, moist air moves over colder sea surface, is called cold sea fog (Koračin et al. 2014). The cold advection fog is relatively thicker than warm advection fog and sometimes the fog top can extend above the inversion base (Huang et al. 2015). The Yellow Sea fog forms when the moist air above a warm branch of the Kuroshio Current is transported northward over the cold Yellow Sea under appropriate synoptic and hydrologic conditions (Huang et al. 2011; Figure 2). One of the synoptic conditions that is related to Yellow Sea fog is the shallow, atmospheric anticyclone over the Yellow Sea region maintained by the land-sea temperature contrast within the marine boundary layer (Koračin et al. 2014). Also, the tidal mixing in the shelf regions lowers the SST and causes the formation of SST fronts, which affect fog dynamics, especially along the Korea coast (Koračin et al. 2017).

Recently, many studies focused on the dynamics of Yellow Sea fog by using atmospheric numerical modeling, which also used to investigate the dense sea fog events when combined with satellite data (Koračin et al. 2017). Based on the numerical simulations, Li et al. (2012) found that the vertical mixing process resulting from the low-level jet contributes to the initial formation of the fog events
over the Yellow Sea. Meanwhile, the coastal terrain conditions also have a significant effect on the intensity of fog.

1.2.2 Seasonal Variations of Yellow Sea Fog

In general, the Yellow Sea fog season begins in April with the occurrence of the basin-scale anticyclone over the Yellow Sea and northern East China Seas and ends in August under the influence of the large-scale shift in the East Asian summer monsoons (Zhang et al. 2009). On average, there are 50 fog days observed between April and July on the Chinese coast (Zhang et al. 2009). Additionally, the Yellow Sea fog season can be further divided into spring (April to May) and summer (July) fogs based on differences in formation mechanisms and occurrence frequency (Zhang et al. 2012). The air-sea temperature difference is one of the main differences between the spring and summer fogs (Yang et al. 2017). The temperature difference between land and sea leads to the formation of a shallow anticyclone over the cooler Yellow Sea in April, the southerly winds on the west of this anticyclone can transport the warm and moist air from the south to the cold Yellow Sea and cause the abrupt beginning of spring Yellow Sea fog; while the summer Yellow Sea fog is related to the East Asian-Western Pacific monsoons, which changes the prevailing wind direction from southerly to easterly (Zhang et al. 2009; Zhang et al. 2012).

During the fog season, the prevailing surface wind direction over the Yellow Sea region is south to southeast from 2 – 10 m/s (Zhang et al. 2009). The spring sea fog is quite shallow with fog thickness below 600 m most of the time; the summer sea fog is relatively deep, with fog thickness reaching 1000 m (Zhang et al. 2012). Stronger turbulence in the lower marine atmospheric boundary layer is observed during the spring sea fog, which indicates that the stability is relatively weaker than summer sea fog (Zhang et al. 2009). There are four directions of airflow paths that lead to the spring sea fog: the northwest, east, southeast, and southwest of the Yellow Sea region, and the spring Yellow Sea fog forms with the surface divergence center located over the Yellow Sea (Huang et al. 2018).
1.2.3 Underlying Surface Heating of Yellow Sea Fog

The thermodynamic and physical processes of sea fog events, which show how the quantities such as underlying surface, temperature contrast, and turbulence, influence the vertical structure, lifetime and dissipation have been well studied (Boutle et al. 2017). The underlying surface conditions change during the sea fog processes. The surface air temperature decreases when fog occurs, the difference between the surface air temperature and sea surface temperature falls between 0.5 to 3 °C due to the cooling effect of the sea surface (B. Wang, 1985).

In general, Yellow Sea fog forms with fog air temperature higher than the SST. Yang et al. (2018) shows that among 216 fog cases during March – July from 2008 to 2015, only one third of the fog cases have the feature with air temperature falls below SST according to the buoy observations.

1.3 Aerosol

Atmospheric aerosols are suspended solid particles, liquid, or mixed particles with variable chemical composition and sizes (Putaud et al. 2010). Aerosol particles are either the primary aerosols, which are emitted directly to the atmosphere, or secondary aerosols, which are produced in the atmosphere from precursors (Myhre et al. 2013).

Atmospheric particulate matter has a major impact on the global climate (Rosenfeld, 2006). Aerosols have both direct and indirect effects on the atmosphere. For the direct effects, aerosols can scatter and absorb solar shortwave and longwave radiation, which can have a cooling or warming effect of the earth and change the radiative balance of the earth-atmosphere system (Myhre et al. 2013). In addition, Albrecht (1989) showed that aerosols can also influence the atmosphere indirectly by changing the properties, amount, and lifetime of cloud through modifying the microphysics processes (Figure 3): (1) the 1st indirect aerosol effect, (2) the 2nd indirect effect, and (3) the semi-direct effect. The 1st indirect effect also known as the cloud albedo effect, or the Twomey effect, it refers to the microphysical induction
effect on the size and number of cloud droplet (Ramaswamy et al. 2001; Lohmann and Feichter 2005; Twomey 1977). The 2nd indirect effect also known as the cloud lifetime effect, or the Albrecht effect, it refers to the microphysical induction effect on the height and lifetime of clouds (Ramaswamy et al. 2001; Lohmann and Feichter, 2005; Albrecht, 1989). The semi-direct effect refers to the impact of heating in the troposphere that is caused by the absorption of shortwave radiation of absorbing tropospheric aerosols. The changes in the humidity and stability of the troposphere caused by the semi-direct effect can lead to the changes of the formation and lifetime of clouds. Specially, the heating at the top of the boundary layer can “burn” away clouds in two ways: (1) accelerate the process of evaporation of clouds, and (2) suppress the upward flow from the surface. The semi-direct effect can heat the air and prevent the solar radiation to reach the surface, which reduces the convection and prevent the formation of new clouds (Hansen et al. 1997).

1.3.1 Aerosol Conditions for Fog

Both fog and aerosols occur most commonly in the planetary boundary layer (Li et al. 2017). Gultepe et al. (2009) showed that the fog droplet number concentration of polluted areas could be ten times larger than clean areas in Canada, which resulted in smaller fog droplet size and lower visibility which is indicative of the 1st indirect effect (Albrecht, 1989).

Previous studies have shown how aerosol influences fog properties and what role aerosols play during fog episodes (Jia et al. 2018; Pant et al. 2010; Beiderwieden et al. 2005; Sasakawa et al. 2002). The physical features of aerosols (such as size distribution, total aerosol number, etc.) change during the fog episodes (Pant et al. 2010). Experimental results show that aerosol size plays a more important role, when acting as CCN (Cloud Condensation Nuclei), than the chemistry of the aerosol (Mazoyer et al. 2019). CCN concentrations have a strong influence on fog lifetime by enhancing the fog top radiation cooling and decreasing the average droplet size (Maalick et al. 2016). The droplet's concentration number is
mainly controlled by supersaturation, which can be limited by activable aerosol concentration (Mazoyer et al. 2019).

1.3.2 SOA & BC

Secondary Organic Aerosol (SOA) refers to molecules produced via oxidation over several generations of parent organic molecules. SOA represent a significant proportion of atmospheric aerosols in the troposphere. The chemistry of SOA formation is complex as atmospheric SOA is a heterogeneous mixture of organic species with various chemical and physical properties. SOA impact weather, climate, the environment, human health and can be related to fog events (Kroll and Seinfeld, 2008).

Higher concentrations of SOA are observed during fog episodes compared with clear days (Kaul et al. 2011). Peak SOA concentrations are observed in the evening for fog days, while peak SOA concentrations are observed in the afternoon for clear days (Kaul et al. 2011).

Black Carbon (BC), also known as soot, is part of fine particulate air pollution (PM2.5). It is formed by the incomplete combustion of fossil fuels, wood and other fuels. After being released into the atmosphere, BC can only last for days to weeks before being lost to the surface via dry or wet deposition. BC has both a direct and indirect influence on the atmosphere. It can influence the atmosphere directly by absorbing the solar radiation and heating the surrounding atmosphere thereby changing the heat budget. It can also influence the atmosphere indirectly by changing cloud properties, rainfall patterns, and regional circulations (Maalick et al. 2016).

1.3.3 Ozone

Air Pollution Information System (APIS) shows that: “ozone (O₃) is a gas composed of three atoms of oxygen. It is present throughout the atmosphere with concentration peaks at two levels: the stratosphere (15 – 50 km) and the troposphere (0 – 15 km). O₃ at different levels has different effects on atmosphere
and human society. The stratospheric \(O_3\) can regulate the transmittance of ultraviolet (UV) light to the earth surface.” \(O_3\) at this level can be depleted by the ozone-depleting substances (ODS), which mainly refers to the manufactured chemicals, especially the manufactured halocarbon refrigerants, solvents, propellants, and foam-blowing agents (chlorofluorocarbons (CFCs), HCFCs, halons). \(O_3\) over the polar regions, when impacted by ODS, can result in an ozone hole, which is of concern regarding the health effects of exposure to increased levels of UV. The United States Environmental Protection Agency (EPA) shows that: “\(O_3\) at the ground level belongs to one of the toxic air pollutants and greenhouse gases, which can affect people’s health and environment. A variety of health problems can be triggered by breathing elevated concentrations of \(O_3\), such as chest pain, coughing, throat irritation, and so on. Also, \(O_3\) can affect sensitive vegetation and ecosystems, including forests, parks and wilderness areas.”

According to the APIS, the ground-level \(O_3\) is not emitted directly, it is a “secondary” pollutant formed by a complicated series of chemical reactions in the presence of sunlight (Figure 4). The APIS also shows that: “The photochemical reactions of from nitrogen oxides (NO\(_x\)) and volatile organic compounds (VOCs) are the main source of \(O_3\) at the ground level. Chemical reactions usually take hours or days instead of happening instantaneously. The \(O_3\) levels at a particular location may arise from VOCs and NO\(_x\) emissions hundreds or even thousands of miles away. Therefore, the maximum \(O_3\) concentrations generally occur downwind of the source area of the precursor pollutant emissions, which mainly comes from the anthropogenic emissions.”

1.3.4 Aerosol Conditions Over the Yellow Sea Area

Due to large fossil fuel consumption, North China suffers from air pollution (Wei et al. 2017). The meteorological conditions that favor the sea fog process also favor the accumulation of aerosols and pollutants (Jia et al. 2018). Due to anthropogenic activities related to industrial emissions and heavy traffic, sulfate and nitrate have become the main secondary aerosol particles in Northern and
Eastern China. The precursors of SO$_2$, NO$_x$ and NH$_3$ have a significant effect on fog formation and microphysics (Jia and Guo, 2012). The ratio of SO$_4^{2-}$ to NO$_3^-$ shows that the emission of SO$_2$ from coal burning has been controlled effectively, while the emission from automobile exhaust has led to a continuous increase in the concentration of NO$_x$ in the atmosphere (Zhang et al. 2013).

The frequency of winter fog events in eastern central China doubled over the past thirty years due to the regional increase in aerosol amount combined with the weakening of the East Asian winter monsoon, which brings less cold and dry air that favors the formation of fog in that region (Niu et al. 2010). For the Yellow Sea region, Zhang et al. (2014) showed that with the process of global warming, the frequency of Yellow Sea fog is decreasing due to a southward shifted in the subtropical high with reduced northward moisture transportation, which also shows that the Yellow Sea fog is not only affected by aerosols, but also the result of the air-sea temperature inversion and appropriate meteorological conditions.

### 1.4 Motivation and Objectives

Historically, research on sea fog focused on synoptic and climatological studies, more recently research has investigated the microphysical processes of sea fog, while other research has used new methods, such numerical simulations or remote sensing observations (Zhang & Bao, 2008). Early research on the synoptic and hydrologic conditions of Yellow Sea fog occurred as far back as 1948, since then, much research focused on the meteorology of Yellow Sea fog from 1970s to 1980s (B. Wang, 1985; Cao et al. 1988). Using observation data and numerical models in sea fog simulations are an important part of studying sea fog. In the 1990s, numerical simulation of sea fog began in China, and the numerical forecast studies of sea fog are typically limited to individual cases (Zhang & Bao, 2008). Analyses using the Weather Research and Forecasting (WRF)/Chem model show that aerosol can influence the fog evolution through the modification of fog properties, microphysics, radiation, and dynamics (Jia et al. 2019). However, there are many potential difficulties in fog modeling and prediction. The lack of in situ observation, the
influence of the different planetary boundary layer schemes, and the uncertainties in the parameterization of turbulence, radiation, and microphysics processes make fog modeling and prediction very challenging (Gao et al. 2007; Pagowski et al. 2004).

Former studies of Yellow Sea fog mainly use datasets from station observations, including surface station observations, soundings, buoy data, ship reports, and reanalysis data from National Centers for Environmental Prediction (NCEP)/National Centers for Atmospheric Research (NCAR), International Comprehensive Ocean-Atmosphere Data Set (ICOADS), and the Japanese 25-year Reanalysis Project (JRA-25) (Gao et al. 2007; Huang et al., 2010; Huang et al. 2018; Zhang et al., 2009; Zhang et al., 2012). With the development of spaceborne remote sensing technology, many studies on Yellow Sea fog use datasets from satellites, including the Multifunctional Transport Satellite (MTSAT), Quik Scatterometer (QuikSCAT), Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), and Moderate Resolution Imaging Spectroradiometer (MODIS) (Wu et al. 2015; Hao 2017; Yang and Gao 2019). Compared with datasets from surface observation stations, satellite data provides a holistic view of the Yellow Sea region and can be used as an efficient method when identifying sea fog cases.

In this study, we use high-resolution data from MODIS Aqua L2 as a tool to identify sea fog cases between 2002-2020 and investigate the relationship between aerosols, cloud properties, and SST in the Yellow Sea region. Expanding on previous research (Wu et al. 2015; Hao 2017), we use aerosol, cloud properties, and SST from MODIS. In addition to the high-resolution data from MODIS we also utilize datasets from the OMI Aura satellite, station observations, and reanalysis data to investigate how pollution, which is increasing in the Yellow Sea area, will impact fog. This work attempts to determine the relationships between aerosol, cloud properties and SST thereby contributing to the improvement of sea fog simulation and prediction.
CHAPTER 2

DATA

Datasets from surface observation stations are used when identifying the sea fog cases. The aerosol, ozone and cloud properties over the Yellow Sea region from satellites are used to study the sea fog events under different aerosol conditions, and the vertical structure of the fog is analyzed with the CALIPSO data. Reanalysis data from NCEP/NCAR are used to study temperature advection around the Yellow Sea area. Due to limited data availability, only days in the fog season (April to August) 2002-2020 are investigated here.

2.1 Surface Station Data

Surface station observations from the NCEI (NOAA National Centers for Environmental Information), recorded every 3 hours, are used to identify Yellow Sea fog cases. Previous research used QD (Qingdao) surface observations to study the seasonal features of sea fog (Zhang et al. 2009). In the current work, six surface stations that near QD (Qingdao) are used to study the sea fog occurrence: QD (Qingdao), CST (Chengshantou), LY (Laiyang), LT (Liuting), QLI (Qianli Island), and SD (Shidao) (Figure 5). Due to the lack of data for some time periods, not all the observations are available for the entire time period of interest. Table 1 shows the years of available data for these six stations. Therefore, the most complete dataset of CST from 1973-2020 is mainly used to select fog cases, combined with other stations.

Bari et al. (2016) showed that fog is indicated when visibility is documented as less than 1 km. A fog day can be defined when fog is observed at least once a day (Koračin & Dorman, 2017). 534 cases from 1946 to 2020 show the visibility less than 1 km. Among them, eight cases are confirmed by other references (Zhang et al. 2012; Wu et al. 2015; Yuan et al. 2016; Li et al. 2012) to be sea fog cases. However, due to unavoidable instrument errors, fog may not be the only reason that causes
visibility less than 1 km. Therefore, other methods are needed to verify these selected cases.

2.2 Soundings

Here, sounding files at 0000 UTC from the website of University of Wyoming are used (http://weather.uwyo.edu/upperair/sounding.html). Only QD station is available near the coast of Shandong peninsula from this data source. The dew point temperature and air temperature of QD soundings are used to study the vertical structures over the northwestern Yellow Sea and identify the height of the temperature inversion.

The temperature inversion height from the sounding files is used to estimate maximum fog thickness. Table 3 shows the temperature inversion heights of all 15 cases. The mean temperature inversion height is 633 m, the max values for all cases fall between 700 to 800 m. Since clouds, other than fog may be included in a particular satellite image (see section 2.3.1) it is necessary to filter the data by Cloud Top Height (CTH) to limit the analysis to only pixels containing fog. In order to select the most appropriate CTH filtering threshold (e.g. max height for fog while eliminating non-fog clouds above the surface), CTH values of the mean temperature inversion height, 700 m, and 800 m are used to for comparison. Figure 6 shows the CTH plot of a fog case on May 13, 2018 using different CTH threshold values. It shows that a CTH of 633 m results in the least complete fog area, with absent values in the middle and east area (even though fog is confirmed in those locations by visual inspection of RGB visible imagery). The fog area is more complete when the maximum CTH is 700 m, but the middle of the fog area is still blank. A CTH maximum value of 800 m includes all details of the fog area. Also, we can see more intuitively from table 2 that CTH of 800 m has the most pixels. Therefore, the maximum CTH of 800 m is used when investigating the fog thickness in the rest of this work.
2.3 Satellite Data

Datasets from several satellites are used here: (1) MODIS L1B Granule Images provides high-definition MODIS data to verify the fog cases, (2) MODIS Aqua high-resolution Level 2 data provides detailed information of aerosol, cloud properties, and SST data (from GHRSST), (3) ozone data from the OMI satellite for confirming the presence of pollution, and (4) the vertical structure information of the sea fog from CALIPSO.

2.3.1 MODIS Aqua Data

MODIS is one of the instruments on board the polar orbiting Aqua satellite (Salomonson et al. 2006) and was launched May 4, 2002. It measures 36 spectral frequencies of light, which provides information of the physical properties of the atmosphere. The Aqua satellite passes within 10 degrees of each pole every orbit and is sun-synchronous such that the satellite passes over the same spot of earth at about the same local time every day. Aqua passes from north to south across the equator in the afternoon (at approximately 1:30 pm) and views the entire surface of earth every 2 days.

Satellite images from MODIS are used to confirm the fog days from the selected 534 cases. During that process, in order to have a better understanding of fog features, only cases showing the entire fog area are selected. Figure 7 shows the satellite images of different fog cases from MODIS Granule RGB Images. The fog area on May 3, 2020 (Figure 7, (b)) shows a case that was not selected due to the fact that the fog area is not fully visible and in the corner of the satellite image. In the second example fog case on July 31, 2020 (Figure 7, (c)), the fog over the Yellow Sea is almost covered by high clouds such that the fog is not visible and is also rejected. Thus, both of these cases cannot provide a clear view of the complete fog area, compared with the fog case on March 28, 2012 (Figure 7, (a)). After careful selection, 15 cases are chosen for this research with complete views of fog events.
over the Yellow Sea, and four of them are sea fog cases confirmed by former studies (May 2, 2008; May 3, 2009; May 4, 2009; March 28, 2012).

High-resolution data sets from MODIS Aqua L2 are used to investigate the relationships between cloud properties, aerosol (AOD, Aerosol Optical Depth, $10 \times 10$ km), and SST features. The specific cloud properties used here are ER (Cloud Effective Radius, $1 \times 1$ km), COT (Cloud Optical Thickness, $1 \times 1$ km), CTT (Cloud Top Temperature, $5 \times 5$ km), and CTH (Cloud Top Height, $5 \times 5$ km). As a supplement, the land-sea mask ($1 \times 1$ km) from MODIS L2 geography file is used here to focus on the sea fog over the ocean area.

High-resolution sea surface temperature (SST, $1 \times 1$ km) data from GHRSSST is used to study the influence of underlying surface heating. The GHRSSST is an open international science group that promotes the application of satellite for monitoring SST (https://www.ghrsst.org). Verification of the MODIS Aqua SST products by using buoy data in the coastal waters of the Yellow Sea has shown that MODIS SST agreed well with buoy observations, though the accuracy for spring and summer is lower than autumn and winter because of the sea fog along the Shandong peninsula (Hao et al. 2017). Figure 8 shows an example of the SST for a fog case on March 28, 2012. As shown in the figure, the SST is lower under the fog area compared with others due to the influence of sea fog coverage.

2.3.2 **OMI Aura Data**

The Ozone Monitoring Instrument (OMI) is a visual and ultraviolet spectrometer that was launched on board of NASA Aura spacecraft on July 15, 2004 (Levelt et al. 2018). The OMI instrument can distinguish between aerosol types, such as smoke, dust, and sulfates, and measures cloud pressure and coverage, which provides data to derive tropospheric ozone (https://aura.gsfc.nasa.gov/omi.html). OMI continues the Total Ozone Mapping Spectrometer (TOMS) record for total ozone and other atmospheric parameters related to ozone chemistry and climate.
Ozone column amount data from OMI is used here to investigate the pollution in the Yellow Sea area. The ozone data is from the level 3 daily global TOMS-Like Total column Ozone gridded product OMIO3d (1 × 1 degree). The OMTO3d product is produced by gridding and averaging the good quality level 2 total column ozone orbital swath data on the 1 × 1 degree global grids. However, instrument issues resulted in several row anomalies (missing data) in early 2007. These increases or decreases of radiance signal affects the quality of the Level 1B and Level 2 data products, but no corrections have yet been made on these data (Torres et al. 2018; OMI Data Products). For the selected Yellow Sea fog cases, only 3 cases have complete ozone data, the other 12 cases have missing data due to the row anomaly (e.g. Figure 9). For the cases with missing data, the pollution conditions are examined by surrounding ozone column amounts.

2.3.3 CALIPSO Data

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) is an environmental satellite that was launched on April 28, 2006. The CALIPSO satellite has three instruments including the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) Lidar, which is a two-wavelength (532 nm/1064 nm) polarization-sensitive Rayleigh-Mei lidar. The CALIOP level 1 data is a set of calibrated attenuated back-scatter profiles at 532 nm and 1064 nm. The 532 nm signals have a vertical resolution of 30 m between 0.5 km and 8.2 km. Vertical feature mask (VFM) is a level 2 product that describes the vertical and horizontal distribution of cloud and aerosol layers observed by CALIOP that is derived from the backscatter data. The ratios of all three lidar channels provide estimates of particle size, particle shape, and differentiate water/ice clouds.

The high-resolution cloud and aerosol vertical profiles provided by CALIPSO can give the vertical structure information of sea fog and low clouds (Wu et al. 2015). It can be a supplemental method when detecting sea fogs by using the passive satellite measurements to confirm where fog occurs. As the CALIPSO satellite only provides a vertical profile of the selected area, data is not available if
the satellite does not pass directly over the fog area. Therefore, the CALIPSO datasets are not complete or available for all cases. Among all 15 sea fog cases, only 8 of them have available CALPSO data (June 8, 2007; May 2, 2008; June 1, 2011; March 28, 2012; April 8, 2014; April 9, 2014; April 14, 2016).

2.4 Reanalysis Data

When analyzing the synoptic conditions of sea fog cases, wind and air temperature data sets are used here to calculate the temperature advection. The daily wind and air temperature data is from the NCEP (National Centers for Environmental Prediction)/NCAR (National Centers for Atmospheric Research) reanalysis dataset of multiple pressure levels. The resolution of wind and temperature data is 2.5 × 2.5 degrees on global grids.
CHAPTER 3

METHODS

3.1 CTH Modification

Though MODIS provides valuable CTH data of high-resolution, the current CTH retrieval algorithms does not suit stratocumulus clouds well (Garay et al. 2008; Harshvardhan et al. 2009; Holz et al. 2008). For low-level clouds, errors occur when identifying CTH under strong temperature inversions in the boundary layer when using the MODIS satellite, especially for marine stratocumulus clouds (Garay et al. 2008; Harshvardhan et al. 2009). These errors usually lead to about 2 km higher measurement than the geometric observation (Harshvardhan et al. 2009).

The correction of CTH product cannot be made by the identification of CTH bias, therefore, other information is needed in order to determine CTH for low-level clouds under strong inversion, such as the assumption of temperature lapse rate below cloud top to the surface, 11 μm brightness temperature and the surface temperature (Harshvardhan et al. 2009). In previous study, a modification using mixing line arguments and incorporation of the typical internal stratification of marine boundary layer was suggested (Wood and Bretherton, 2004). Harshvardhan et al. (2009) found that the lapse rate in units of kelvin per kilometer from the SST to the cloud top can be well represented by equation 3.1. Many studies cited Harshvardhan’s work when studying the CTH of the stratocumulus region (Zuidema et al. 2009; Painemal and Zuidema 2011; Costantino and Bréon 2013). Therefore, this modification is used in the study to reduce potential errors in the CTH data:

\[
\frac{SST - T_{top}}{CTH} = 9.2 \exp \left[ - \left( \frac{CTH}{4.8} \right)^2 \right] \quad (\text{eq. 3.1})
\]
Where $T_{top}$ is the actual CTT, SST is surface temperature in the ocean area filtered by the land-sea mask. The modified CTH is in Figure 10, which is about 100-200 meters lower compared to the original one.

### 3.2 CTH Interpolation

The resolution of the various products included in the MODIS dataset are different. For example, the resolution of CTH is 5 km, which is relatively lower compared with ER, whose resolution is 1 km. The GriddedInterpolant in MATLAB is used here to make all the data products the same resolution (1 × 1 km). Figure 11 shows the original CTH and the CTH after interpolation for a fog case on May 23, 2006.

### 3.3 Fog Area Selection

We can see from Figure 12 that there are some CTH values around Bohai Bay, which can be identified as pollutants instead of sea fog according to the satellite image. It means that CTH picks up not only fog and cloud, but pollution as well. Therefore, when it comes to the selection of fog areas, both CTH and ER are used to identify and select fog pixels. Figure 12 shows the satellite image and ER, CTH for a fog case on May 3, 2009. For this case, the sea fog covers almost the entire Yellow Sea area, combined with the cloud on the south and north area. In this example, ER for this case clearly shows the details of the cloud where the ER values are smaller for fog compared with the cloud area in the south.

According to the result of soundings, most of the fog cases have fog thickness to be around 800 m. By setting the maximum CTH as 800 m, upper-level clouds are excluded. This allows for the selection of the fog area in the Yellow Sea, while the non-fog cloud in the south and north can be filtered out. Finally, by applying the CTH mask combined with the land-sea mask, the cloud ER of the whole fog area over the Yellow Sea fog can be selected without terrestrial or upper-level cloud contamination.
CHAPTER 4

RESULTS

Datasets from OMI Aura and MODIS Aqua are used to investigate the aerosol conditions over the Yellow Sea region. Additional analyses are conducted to investigate the specific relationship between cloud properties, aerosols, and SST. In general, this study shows that the formation of Yellow Sea fog is the result of both suitable synoptic and aerosol conditions. The difference of aerosol features will result in the different sea fog pattern. In other words, the characteristics of Yellow Sea fog is different under varying aerosol conditions.

4.1 Ozone Column Concentration

Ozone column concentration from the OMI Aura L2 dataset is used to investigate the pollution conditions in the Yellow Sea region. Figure 13 shows that there are some blank bands of the satellite tracks from 2009 due to the row anomalies. For these cases with absent values in the Yellow Sea area, the ozone information is investigated based on the surrounding ozone column concentrations. Ozone is measured as the total column amount by OMI in Dobson unit (DU), which refers a unit used in the measure of the column abundance of ozone in the atmosphere (American Meteorology Society). A typical Dobson reading for the ozone layer is about 300 DU, which also refers to the average amount of ozone in the atmosphere (Herschy et al. 1998). The ozone column concentration is higher in Northeastern China, with ozone column amount larger than 300 DU, and some cases even reaches 400 DU. While for the south plain of China, the ozone column amount is around the average level. As the precursors of \( O_3 \) mainly come from the anthropogenic emission, the larger concentration of \( O_3 \) column amount in Northeastern China confirms the higher pollution conditions caused by human activities.
4.2 Terrestrial Aerosol Type

Dataset from the MODIS Aqua L2 aerosol file is used to investigate the terrestrial aerosol types around the Yellow Sea area. We can see from Figure 14 that there are two main aerosol types around the Yellow Sea area, sulfate and heavy absorbing smoke. Out of the 15 selected cases, 12 cases have sulfate as the main aerosol type. Northeastern China is highly developed with numerous industrial and chemical complexes and cites, which produce sulfate pollution. The main terrestrial aerosol type for the other three cases is heavy absorbing smoke, combined with the sulfate and dust in the inland area which are discussed separately below in section 4.2.1.

4.2.1 Fire Cases

Different from the other 12 sea fog cases with sulfate as the main terrestrial aerosol type, the main terrestrial aerosol type for cases on June 8, 2007, June 1, 2011, and June 6, 2018 is heavy absorbing smoke, which is caused by the confirmed fire occurrences around Shandong Peninsula. Therefore, these three cases are called “fire cases”.

Figure 15, (a) shows the fire occurrence, as identified by thermal emissions, on June 8, 2007. Note that this data only shows where fires occur, not how large (area burned) or how intense they are with regard to smoke production or thermal emission. The density of fire occurrence in the south of the Shandong Peninsula corresponds with the pollutant band in the middle of the fog area (Figure 15, (c)). There is also higher aerosol concentration in that area (Figure 15, (b)). Note that AOD data in the south is absent due to the coverage of clouds. The wind speed in the Yellow Sea region is lower than surrounding area (Figure 15, (d)), which can be one of the reasons that contributes to the high concentration of the heavy absorbing smoke around Shandong Peninsula. Also, the weak southwesterly wind in the south Shandong Peninsula can transport the heavily absorbing smoke to the Yellow Sea region.
Yellow Sea fog on June 1, 2011 is another case with fire occurring near Shandong Peninsula (Figure 16, (a)). In the visible RGB satellite image, the pollutant band is also very clear south of the fog area (Figure 16, (c)) and corresponds to the higher AOD concentration in the south of the Yellow Sea area (Figure 16, (b)). The wind speed in the Yellow Sea region is also lower than surrounding area and from the southeast direction (Figure 16, (d)), potentially transporting the heavy smoke to the Yellow Sea area.

The third heavy absorbing smoke case occurs on June 6, 2018 (Figure 17). From the NASA World image (Figure 17, (a)), we can see that the fires separate in the south and west of the Shandong Peninsula. However, no obvious pollution area can be identified from the MODIS visible satellite image (Figure 17, (c)) compared with the other two cases thermal emissions indicative of fire activity. This is likely due the strong southerly wind in the Shandong Peninsula (Figure 17, (d)). The weak westerly and southwesterly wind that carries the aerosols from the fire locations encounters the stronger southerly wind and spreads the heavy absorbing smoke to the Shandong Peninsula and Bohai Bay. Larger AOD concentrations can also be found around Yellow Sea area, but the value is relatively smaller compared with the other two cases.

4.3 Relationship Between Cloud Properties, Aerosols, and SST

Previous studies have shown that increased AOD is strongly correlated with increases in CTH, which is also evidence for aerosol invigoration of convective clouds (Szczodrak et al. 2001). By increasing the number and decreasing the size of cloud droplets, and suppressing precipitation in the liquid phase, aerosols may be able to increase latent heat release from the freezing of cloud water, increasing the buoyancy of cloud parcels resulting in the invigoration of convective clouds (Szczodrak et al. 2001). Furthermore, a strong correlation is found between COT and ER, especially for marine stratocumulus clouds (Szczodrak et al. 2001).
SST plays an important part in the formation and maintenance mechanism of sea fog. For Yellow Sea fog, the colder shelf regions caused by the tidal mixing can result in a higher frequency of sea fog along the Korean coast of the Yellow Sea and longer fog season (Su and Su 2009; Ma et al. 2004; Cho et al. 2000). Also, the upwelling and cold SST combined with the northwesterly wind is responsible for the fog formation in the warm season (May – October), and the SST is found to be higher than air temperature when the sea fog caused by stratus lowering occurs in the cool season (November – April) along California coast (Byers 1930; Sverdrup and Fleming 1941; Sverdrup et al. 1942; Leipper 1948; Koračin et al. 2001; Lewis et al. 2003, 2004).

However, the analysis completed here does not show strong correlations between the individual cloud properties and aerosol or SST for the selected 15 sea fog cases. High-resolution aerosol data co-located with the fog (cloud data) is not available, therefore the direct comparison between the two properties cannot be made. Therefore, the mean values of aerosol data of the Yellow Sea and cloud properties of the fog area are used to categorize and analyze the fog cases. Table 3 shows the mean values of the AOD, COT, ER and SST for the 15 selected cases. The cases are ranked according to the mean AOD values from lowest to highest. Ranking by other variables did not produce any clear patterns or relationships. The aerosol loading in this region is relatively high with many cases having similar values. Also, we attempt to highlight the pollution and clear days, but it turns out that the Yellow Sea area is all polluted, which is confirmed by the OMI results.

Results show that the scene mean values are not a high enough resolution to show any relationship between the mean AOD, COT, ER and SST values, except some differences caused by the synoptic conditions. For example, the difference in SST is mainly caused by seasonal variation. The earliest month of the sea fog case is March, where the sea water is relatively cooler compared with June due to the difference in solar radiation intensity. Therefore, in order to exclude the seasonal changes influence on our study, CTH, ER and COT are selected to further study the
relationship between the cloud properties, aerosol, and SST. Here, we use a bi-variate comparison method to use to look at the variations between these three variables simultaneously.

4.4 Bi-Variate Comparison

Figure 18 shows the result of the bi-variate comparison of CTH, ER and COT. For most of the figures, there is what will be referred to hereafter as the “Diagonal Pattern” with larger COT values in the upper left and lower values in the bottom right. However, some cases show different patterns, such as the fog case on June 8, 2012, May 2, 2008. According to their difference observed relationships, these 15 cases are divided into 3 types, the Diagonal Pattern, Left-Right Pattern, and the Inverse-Diagonal Pattern. The Diagonal Pattern refers to the distribution with larger COT values in the upper left and lower values in the bottom right. The Left-Right Pattern refers to the distribution with larger COT values in the left and lower values in the right. The Inverse-Diagonal Pattern refers to the distribution with larger COT values in the upper right and lower values in the bottom left.

4.4.1 Diagonal Pattern

Among the 15 sea fog cases, 11 of them have the diagonal pattern (Figure 19). It indicates that larger values of COT are related to smaller ER and higher CTH. Pollution levels in the Yellow Sea area is relatively higher, resulting in a greater proportion of smaller droplets in fog (Gultepe et al. 2009). The smaller fog droplets can result in a thicker fog and relatively larger cloud optical thickness. The Diagonal Pattern is the most common pattern among all these sea fog cases and is indicative of the 1st indirect effect, even though we cannot evaluate the impact of AOD directly.

We take the fog case on March 28, 2012 as an example to analyze the detailed information regarding the relationship between fog thickness, cloud optical thickness, and droplet effective radius. Figure 20, (a) shows that the CALIPSO satellite passed over the Yellow Sea providing vertical information of this case. The
yellow box in the 532 nm backscatter image (Figure 20, (b)) shows the vertical slice of Yellow Sea area. We can see that the thin white line that connects with the surface is the fog area. Also, the VFM figure (Figure 20, (c)) shows that the orange area indicates that the aerosols are mainly in the troposphere along with clouds.

The bi-variate comparison for the sea fog case on March 28, 2012 shows a standard diagonal pattern, which means that the COT reaches the maximum values when the CTH is higher, and ER is smaller. Figure 21 shows these three variables separately. We find that the cloud top height is relatively larger at the middle of the sea fog area (Figure 21, (a)). It corresponds to the smaller droplet ER values and larger COT at that area. For the south part of the fog area, the ER values are relatively larger, the bigger droplets result in thinner fog corresponding with smaller COT values at that area.

We can see from Figure 14 that the main terrestrial aerosol type for the fog case on March 28, 2012 is sulfate, which is caused by general industrial emissions. There is a clear pollutant band in the middle of the fog area from the satellite image (Figure 7, (a)), which is corresponding to the larger AOD values at that area (Figure 22, (a)). This pollutant band is likely the reason that causes the smaller fog droplets in the middle of the fog area, which results in the relatively thicker fog at that area. The easterly wind is weak in this area on this day and can explain the formation of this pollutant band over the Yellow Sea area.

4.4.2 Left-Right Pattern

Figure 23 shows two fog cases on May 2, 2008 and April 10, 2016, with the Left-Right Pattern. Compared with the Diagonal Pattern, larger COT is corresponding to smaller ER but also smaller CTH for the Left-Right Pattern. For these two cases, smaller fog droplets result in the thinner fog, which is unexpected considering 1st indirect effect.

Figure 24 shows the CTH plot of these two cases. The cloud top height is lower for these two cases with many 0 values in most of the fog areas. It can result in the
CTH data absent when doing the bi-variate analysis. This results in large COT values concentrated at the bottom left corner where CTH ranges from 0 to 200 m. Therefore, for the Left-Right Pattern, the CTH is relatively lower for smaller ER values when the COT is relatively larger.

### 4.4.3 Inverse Diagonal Pattern

Figure 25 shows the Inverse-Diagonal Pattern. In this situation larger values of COT are correlated with both larger ER and higher CTH.

As an example of the Inverse-Diagonal Pattern, Figure 26 shows the CTH, ER, and COT for a fog case on June 8, 2007. This case is also a “fire case” with fire locations on the south of Shandong Peninsula. Due to the influence of fire, there is a clear pollutant band in the middle of the fog area in the visible satellite image (Figure 15, (c)), and the AOD value is higher over that area. The fog area can be divided into two different parts by the pollutant band. For the north part, there is less pollution, and the ER is larger. While the south part is more polluted, and the droplet ER values are smaller around the pollutant band.

Previous studies showed that the meteorological conditions that favor the sea fog process also favor the accumulation of aerosols and pollutants (Jia et al. 2018). The droplet ER is smaller for fog compared with clouds, especially in polluted areas (Gultepe et al. 2009). Generally speaking, droplet ER is negatively correlated with CTH (Suzuki et al. 2011). It means that the smaller ER in the south part of the fog area (Figure 26, (b)) would be expected to correspond with larger CTH in that area. However, the CTH is relatively lower in that area, opposite of what we would expect due to the 1st indirect effect. Thus, this case suggests that the Semi Direct Effect/Cloud Burning Effect of Soot is responsible for the observed relationship. The underlying physics is that the aerosols will absorb sunlight and increase air temperature relative to the temperature of the surface when the boundary layer becomes filled with dark-colored particles (Ackerman et al. 2009 & Hansen et al. 1997). This heating at the top of the boundary layer can burn away (evaporate)
clouds (Ackerman et al. 2009). In this fog case, the heavy absorbing smoke that is produced by the fires in the south of Shandong Peninsula is potentially warming air in the boundary layer and evaporation or reducing the fog over that area. That is a potential explanation for the fog being thinner near main band of aerosols rather than thicker as in the Diagonal Pattern cases.

Among these three sea fog cases with confirmed fire occurrence around Shandong Peninsula, two cases (June 8, 2007; June 6, 2018) show the Inverse-Diagonal Pattern while the fog case on June 1, 2011 does not. Figure 27 shows the vertical structure of air temperature and dew point temperature of QD station from soundings. We can see from the sounding that both fog cases on June 8, 2007 and June 6, 2018 show the temperature inversion around 700 m. The dew point temperature and temperature are closer near the surface, which indicates that the moisture is present. However, there is no obvious temperature inversion for the fog case on June 1, 2011, and the boundary layer is dryer.

Figure 28 shows the temperature advection for the three “fire cases”. We can see that both the fog cases on June 1, 2011 and June 8, 2007 show cold advection in the Shandong Peninsula. For the fog case on June 8, 2007, there is weak warm advection in the Yellow Sea area with strong cold advection in the north of Yellow Sea. While we can only find weak cold advection in the west of Yellow Sea area with warm advection in the north of Bohai Bay for fog case on June 1, 2011. For the fog case on June 6, 2018 (Figure 28, (c)), we can see that there is strong warm advection in Yellow Sea area that corresponds with cold advection in the middle plain of China. By comparing these three cases, we can find that there is no strong temperature difference from the North and South Yellow Sea for the fog case on June 1, 2011.

Besides, both the fog cases on June 1, 2011 and June 8, 2007 show the weak wind compared with the strong southerly wind in the fog case on June 6, 2018, which can transport the heavy absorbing smoke out of Shandong Peninsula.
However, fog case on June 1, 2011 has the lowest mean AOD concentration over Yellow Sea area (Table 3), which may not be enough for the Semi Direct Effect/Cloud Burning Effect of Soot to impact the fog as it requires sufficient amount of aerosol (Hansen et al. 1997; Ackerman et al. 2000; Maalick et al. 2016).

Though there are fires identified around Shandong Peninsula, the drier boundary condition and weak temperature advection combined with lower AOD concentration cannot trigger the Semi Direct Effect/Cloud Burning Effect of Soot for the fog case on June 1, 2011. Therefore, the bi-variate comparison of the fog case on June 1, 2011 shows the Diagonal Pattern. While for the other two “fire cases”, the strong temperature difference, good moisture condition in the boundary layer and sufficient aerosol combine together to favor the formation of sea fog and create the appropriate conditions for the Semi Direct Effect/Cloud Burning Effect of Soot to occur and contribute to the Inverse-Diagonal Pattern.

4.4.4 Sum Bi-Variate Comparison

Figure 29 shows the combined bi-variate comparison of all 15 fog cases. When looking at it in detail, we can find that there are some larger COT values on the bottom left corner that are due to the zero values for the two cases of the Left-Right Pattern. The larger values of COT in the upper middle are indicative of the Semi Direct Effect/Cloud Burning Effect of Soot for these two “fire cases” with the Inverse-Diagonal Pattern. Overall, this figure shows a Diagonal Pattern with the larger values of COT related to both smaller ER and higher CTH in the dominate pattern in the Yellow Sea region.
CHAPTER 5
CONCLUSION AND DISCUSSION

5.1 Conclusions

This study uses various datasets including surface observation stations, satellites, and reanalysis models to investigate fog characteristics under different aerosol conditions for a total of 15 sea fog cases. The study differs from previous studies by utilizing high-resolution data from MODIS Aqua L2 to investigate the relationship between aerosols, cloud properties, and SST. The high-resolution data provides a more detailed and holistic view of the Yellow Sea area of each event rather than a single point from fixed surface observation station or a narrow slice from the airplane. Due to this, this high-resolution data from satellites can serve as a supplement to the surface observation data when identifying sea fog cases.

This study shows that satellite data can be a new tool when investigating how pollution, which is increasing in the Yellow Sea region, will impact fog. Due to industrial emissions and traffic, the pollution conditions in the region are complicated. This study shows evidence of two types of pollutants (sulfate and heavy absorbing smoke) and investigates the conditions of these cases thoroughly. The main terrestrial aerosol type is sulfate caused by industrial emission. Due to the limitation in the data, not all variables provided by satellites can be used. Due to the seasonal variation, some variables such as the SST will change and cannot be used to study the relationship with other variables independently. Therefore, after careful selection, this study excludes variables like SST and uses CTH, ER and COT for the analysis. We compare these three variables simultaneously in order to investigate the impact of background aerosol type on cloud properties. Our conclusions are as follows:

- 15 Yellow Sea fog cases are selected by using the surface observation data combined with the MODIS L2 Granule Images. Sounding files are used
as a supplement method to investigate the thickness of fog. The maximum fog top height falls between 700 m and 800 m. Results show that combined with cloud top height data, the effective radius can filter out the cloud and isolate the sea fog over the Yellow Sea effectively.

- Ozone column concentrations over Yellow Sea area as observed by OMI confirms that the pollution levels in that area is relatively higher than Southern China.

- Aerosol data from MODIS L2 shows that there are two types of terrestrial aerosol for the Yellow Sea area: the sulfate caused by industrial emissions and the heavy absorbing smoke caused by fires. Pollutant bands can be observed in the visible satellite images corresponding with larger AOD values.

- The analysis does not show strong correlations between individual cloud properties and aerosol or SST for the selected 15 sea fog cases.

- The results of the bi-variate comparison between CTH, ER and COT indicate three distinct relationship patterns to their difference in distribution. We term them the Diagonal Pattern, the Left-Right Pattern, and the Inverse Diagonal Pattern.

- Among all the 15 cases, 11 cases show the Diagonal Pattern with larger COT on the upper left and smaller COT on the bottom right. It means that larger values of COT are related to both smaller ER and higher cloud height.

- Two cases show the Left-Right Pattern, which means that the larger COT values are related to smaller ER but lower clouds. The CTH values of these two cases are lower compared with other cases, and the CTH values are even zero for some areas.
• The Inverse-Diagonal Pattern indicates that the larger COT values are related to both higher CTH and larger ER. There are two cases of the Inverse-Diagonal Pattern and both of them are the “fire cases”.

• Two “fire cases” show the Inverse-Diagonal Pattern, which means that the larger COT values are related to both larger ER and higher clouds. Under the influence of the Semi Direct Effect/Cloud Burning Effect of Soot, the absorbing aerosol caused by fires around Shandong Peninsula absorbs the sunlight and increase the temperature of the air in the boundary layer, which can “burn” away clouds and result in fog thinning (cloud evaporation). This thinner fog and smaller ER in the south of the fog area corresponds with smaller COT and results in the formation of the Inverse-Diagonal Pattern.

• Another “fire case” on June 1, 2011 shows a Diagonal Pattern. The synoptic conditions show that there is no obvious temperature inversion and weak temperature difference compared with the other two “fire cases”. The unfavorable synoptic conditions combined with insufficient aerosol amounts cannot trigger the Semi Direct Effect/Cloud Burning Effect of Soot.

• The bi-variate comparison combined the features of all 15 cases shows a Diagonal Pattern. Though more cases are needed in order to make a claim of the conclusion of the bi-variate comparison.

5.2 Future Work

The results and conclusions in this study shows the impacts of different aerosol conditions on the characteristics of sea fog. These findings lead to further questions and indicate the need for additional research on Yellow Sea fog and aerosol interactions:
• Due to limitations of current satellite remote sensing instruments, a better estimate of aerosol types over the yellow sea is needed in order to further study the aerosol conditions for Yellow Sea fog.

• Synoptic conditions are another factor that influence the fog pattern over Yellow Sea area that need further investigation. This study briefly shows how the synoptic conditions can influence fog thickness for these “fire cases”. This suggests that a deeper analysis of synoptic conditions for all cases has the potential to reveal further insight into fog formation and occurrence in the Yellow Sea.

• Evidence of Semi Direct Effect/Cloud Effect of Soot on sea fog for three cases suggest this as another area for future research if more cases can be analyzed.

• The granule mean of SST for each fog event cannot intuitively show the role of SST in Yellow Sea fog events. Therefore, more research can be made to study the relationship between SST, aerosols and cloud properties by using the bi-variate comparison.

• For future work, the relationship revealed by the bi-variate comparison may help with the process of using aerosols to modulate the fog evolution and contribute to the improvement of sea fog simulation and prediction.

• A classification algorithm (or principal component analysis) can be used when classifying the patterns of the bi-variate comparison if more cases are available. By applying these algorithms, the classification process of the bi-variate comparison distributions can be more effective, and the results may show some additional characteristics.
Table 1. Six surface observation stations in Shandong Peninsula and years for which data is available.

<table>
<thead>
<tr>
<th>Station</th>
<th>Available Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chengshantou</td>
<td>1973-2020</td>
</tr>
<tr>
<td>(37.4 °N, 122.7 °E)</td>
<td></td>
</tr>
<tr>
<td>Laiyang</td>
<td>1973-1999</td>
</tr>
<tr>
<td>(37 °N, 120.7 °E)</td>
<td></td>
</tr>
<tr>
<td>Liuting</td>
<td>1994-2002</td>
</tr>
<tr>
<td>(36.3 °N, 120.4 °E)</td>
<td></td>
</tr>
<tr>
<td>Qianli Island</td>
<td>1962-1985</td>
</tr>
<tr>
<td>(36.2 °N, 121.2 °E)</td>
<td></td>
</tr>
<tr>
<td>Shidao</td>
<td>1957-1961</td>
</tr>
<tr>
<td>(36.5 °N, 122.3 °E)</td>
<td></td>
</tr>
<tr>
<td>Qingdao</td>
<td>1946-1948</td>
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<tr>
<td>(36.1 °N, 120.4 °E)</td>
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Table 2. Pixel amounts of CTH data at the mean temperature inversion height (633 m), 700 m and 800m for the 15 sea fog cases.

<table>
<thead>
<tr>
<th>Fog Cases</th>
<th>Pixels of CTH at 633 m</th>
<th>Pixels of CTH at 700 m</th>
<th>Pixels of CTH at 800m</th>
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<tr>
<td>2006.05.23</td>
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<td>20376</td>
<td>21435</td>
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<td>2007.06.08</td>
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<td>2008.05.02</td>
<td>19563</td>
<td>19676</td>
<td>23398</td>
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<td>2009.05.03</td>
<td>4738</td>
<td>7491</td>
<td>7840</td>
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<td>2009.05.04</td>
<td>8680</td>
<td>13696</td>
<td>13907</td>
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<td>2011.05.17</td>
<td>19072</td>
<td>21151</td>
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<td>2011.06.01</td>
<td>5025</td>
<td>5508</td>
<td>6525</td>
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<td>2012.03.28</td>
<td>20746</td>
<td>24841</td>
<td>25140</td>
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<tr>
<td>2014.04.08</td>
<td>14661</td>
<td>17442</td>
<td>18237</td>
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<tr>
<td>2014.04.09</td>
<td>17067</td>
<td>22770</td>
<td>22878</td>
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<td>2018.06.06</td>
<td>8281</td>
<td>8302</td>
<td>9554</td>
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Table 3. Granule mean AOD, COT, ER, SST values of the Yellow Sea area and mean temperature inversion height of QD station for the 15 selected sea fog cases.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Mean AOD</th>
<th>Mean COT</th>
<th>Mean ER (Micron)</th>
<th>Mean SST (°C)</th>
<th>Temperature Inversion Height (m)</th>
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<tr>
<td>2009.05.04</td>
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<td>9.7006</td>
<td>7.7972</td>
<td>10.6673</td>
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<td>2016.04.14</td>
<td>0.5102</td>
<td>9.3236</td>
<td>8.1057</td>
<td>7.9965</td>
<td>763</td>
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<tr>
<td>2011.06.01</td>
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<td>8.6431</td>
<td>8.4656</td>
<td>14.3343</td>
<td>Nan</td>
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<tr>
<td>2011.05.17</td>
<td>0.5296</td>
<td>10.1061</td>
<td>7.7874</td>
<td>13.0364</td>
<td>754</td>
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<tr>
<td>2018.06.06</td>
<td>0.5488</td>
<td>8.0181</td>
<td>8.1329</td>
<td>15.8386</td>
<td>762</td>
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<tr>
<td>2009.05.03</td>
<td>0.5596</td>
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<td>8.464</td>
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<td>166</td>
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<tr>
<td>2012.03.28</td>
<td>0.5626</td>
<td>8.5409</td>
<td>8.4318</td>
<td>8.1441</td>
<td>211</td>
</tr>
<tr>
<td>2014.04.09</td>
<td>0.6189</td>
<td>10.4064</td>
<td>7.4462</td>
<td>8.0927</td>
<td>798</td>
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<tr>
<td>2018.05.13</td>
<td>0.7091</td>
<td>7.7615</td>
<td>7.6294</td>
<td>11.5593</td>
<td>732</td>
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<td>2008.05.02</td>
<td>0.7559</td>
<td>7.3513</td>
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<td>13.2741</td>
<td>749</td>
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<td>2016.04.10</td>
<td>0.7614</td>
<td>13.8427</td>
<td>8.2615</td>
<td>8.3672</td>
<td>759</td>
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<td>2014.04.08</td>
<td>0.7639</td>
<td>8.4725</td>
<td>7.4141</td>
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<td>795</td>
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<td>2007.06.08</td>
<td>0.907</td>
<td>8.4842</td>
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<td>751</td>
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<td>2006.05.23</td>
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<td>9.5122</td>
<td>8.4959</td>
<td>11.2939</td>
<td>756</td>
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<td>2016.04.13</td>
<td>0.9905</td>
<td>9.1233</td>
<td>8.8142</td>
<td>8.9151</td>
<td>711</td>
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Figure 1. Schematic diagram showing the formation of advection type sea fog. Warm moist air is advected off the land surface in a stable layer. The cold sea cools the warm air, which allows condensation to occur. Longwave radiative cooling above the boundary layer continuously keeps the lower atmosphere stable. The condensed water vapor in the stable boundary layer makes it possible for sea fog to occur.

(https://sites.google.com/a/illinois.edu/sea-fog/formation-mechanisms/-1-advection-sea-fog)
Figure 2. Schematic diagram showing oceanic currents adjacent to the Korean Peninsula (Naganuma, 1973; Inoue, 1974).
Figure 3. Schematic diagram showing the mechanisms of the relationship between cloud effects and aerosols. The small black dots represent aerosol particles, and the larger open circles represent cloud droplets. The straight lines represent the incident and reflect solar radiation; and wavy lines represent terrestrial radiation. The filled white circles indicate cloud droplet number concentration (CDNC). The vertical grey dashes represent rainfall, and LWC refers to the liquid water content. (https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-4.html, modified from Haywood and Boucher, 2000)
Figure 4. Schematic diagram showing the source and sinks of O\textsubscript{3} in the troposphere. Annual global fluxes of O\textsubscript{3} calculated using a global chemistry-transport model have been included to show the magnitudes of the individual terms. These fluxes include stratosphere to troposphere exchange, chemical production and loss in the troposphere and the deposition flux to terrestrial and marine surfaces.

Figure 5. The location of the six surface observation stations.
Figure 6. MODIS Aqua L1B Granule Image of a fog case on May 13, 2018 (a), and CTH plots of mean temperature inversion height, 700 m, 800 m: (b) CTH plot of mean temperature inversion height; (c) CTH plot of 700 m; (d) CTH plot of 800 m.
Figure 7. MODIS Aqua L1B Granule Image, fog cases comparison: (a) Fog Cases on March 28, 2012, “good case”; (b) May 3, 2020, “incomplete” fog area; (c) July 31, 2020, fog area covered by high cloud.
Figure 8. An example of the SST data plot at 1 km resolution from GHR SST for a fog case in March 28, 2012, which shows that SST is relatively lower under the coverage of sea fog.
Figure 9. An example of the ozone column concentration plot from OMI Aura L2 dataset, showing the ozone data in Dobson Unit. The white bands on the satellite track indicates the missing data resulting from the row anomalies.
Figure 10. An example of CTH modification for the fog case on May 23, 2006: (a) The original CTH plot; (b) The modified CTH plot.
Figure 11. An example of CTH interpolation for the fog case on May 23, 2006: (a) The original CTH plot of 5 km resolution; (b) The interpolated CTH plot of 1 km resolution.
Figure 12. Fog selection method of fog case on May 3, 2009: (a) MODIS Aqua L1B Granule Image for May 3, 2009 at 0530Z; (b) Non-filtered ER plot at 1 km resolution from MODIS Aqua L2 cloud data product; (c) CTH plot of 800 m at 5 km resolution from MODIS Aqua L2 cloud data product; (d) Result of the ER for the selected fog area after applying the CTH mask and land-sea mask.
Figure 13. Ozone column concentration from OMI Aura L2 dataset for the fog case on May 3, 2009, showing the ozone data in Dobson Unit. The white bands on the satellite track indicates the missing data resulted from the row anomalies.
Figure 14. Terrestrial aerosol types surrounding the Yellow Sea region from the MODIS Aqua L2 aerosol data product. The main terrestrial aerosol type for the first 12 sea fog cases is sulfate, and for the last 3 sea fog cases is heavy absorbing smoke.
Figure 15. Fog case with fire occurrences around Shandong Peninsula on June 8, 2007: (a) Thermal indicators of fire from NASA World View; (b) AOD plot from MODIS Aqua L2 aerosol data product; (c) Satellite RGB visible image from MODIS L1B Granule Image; (d) Wind plot of 995 hPa of 10 m/s unit from NCEP/NCAR reanalysis dataset.
Figure 16. Fog case with fire occurrences around Shandong Peninsula on June 1, 2011: (a) Thermal indicators of fire from NASA World View; (b) AOD plot from MODIS Aqua L2 aerosol data product; (c) Satellite RGB visible image from MODIS L1B Granule Image; (d) Wind plot of 995 hPa of 10 m/s unit from NCEP/NCAR reanalysis dataset.
Figure 17. Fog case with fire occurrences around Shandong Peninsula on June 6, 2018: (a) Thermal indicators of fire from NASA World View; (b) AOD plot from MODIS Aqua L2 aerosol data product; (c) Satellite RGB visible image from MODIS L1B Granule Image; (d) Wind plot of 995 hPa of 10 m/s unit from NCEP/NCAR reanalysis dataset.
Figure 18. Bi-variate comparison for 15 fog cases. The X-axis refers to the ER, the Y-axis refers to the CTH, and the colormap refers to the COT.
Figure 19. The 11 cases of Diagonal Pattern, which refers to the distribution with larger COT values correspond with smaller ER values and larger CTH values. The X-axis refers to the ER, the Y-axis refers to the CTH, and the colormap refers to the COT.
Figure 20. CALIOP/CALIPSO Images of the Yellow Sea area on March 28, 2012 from 04:56:04.4 UTC to 05:09:33 UTC. (a) The green line shows the track of CALIOP/CALIPSO satellite during that time. (b) The corresponding 532 nm Total Attenuated backscatter image, where the yellow box from 34.22 N, 124.84 E to 40.28 N, 123.03 E shows the vertical structure of the sea fog area (white line near the surface). (c) The corresponding Vertical Feature Mask (VFM) image, where the yellow box from 34.22 N, 124.84 E to 40.28 N, 123.03 E shows the tropospheric aerosol (orange) and low clouds (purple) interacting within the lowest 4 km.
Figure 21. Cloud properties and aerosol plots of sea fog case on March 28, 2012 from MODIS Aqua L2 data: (a) CTH plot; (b) ER plot (micron); (c) COT plot.
Figure 22. Aerosol and wind plots of sea fog case on March 28, 2012: (a) AOD plot from MODIS Aqua L2 aerosol data product; (b) Wind plot from NCEP/NCAR reanalysis dataset.
Figure 23. The 2 cases of Left-Right Pattern, which refers to the distribution with larger COT values correspond with larger ER values and smaller CTH values. The X-axis refers to the ER, the Y-axis refers to the CTH, and the colormap refers to the COT.
Figure 24. CTH plots from the MODIS Aqua L2 cloud data product: (a) fog case on May 2, 2008; (b) fog case on April 10, 2016. The absent fog areas are due to the zero values in the CTH data products.
Figure 25. The 2 cases of Inverse-Diagonal Pattern, which refers to the distribution with larger COT values correspond with both larger ER values and larger CTH values. The X-axis refers to the ER, the Y-axis refers to the CTH, and the colormap refers to the COT.
Figure 26. Cloud properties and aerosol for the sea fog case on June 8, 2007 from the MODIS Aqua L2 cloud data: (a) CTH plot; (b) ER plot (micron); (c) COT plot.
Figure 27. Vertical structures of air temperature (blue line) and dew point temperature (red line) from Sounding files at Qingdao Station. (a) Sea fog case on June 1, 2011. (b) Sea fog case on June 8, 2017. (c) Sea fog case on June 6, 2018.
Figure 28. Temperature advection plots calculated from the NCEP/NCAR reanalysis data, where the black line indicates the geographical height at 1000 mb, the black arrow indicates the wind direction and speed of 10 m/s unit, the red area indicates the warm temperature advection, the blue area indicates the cold temperature advection. (a) Sea fog case on June 1, 2011. (b) Sea fog case on June 8, 2017. (c) Sea fog case on June 6, 2018.
Figure 29. Bi-variate comparison of the 15 fog cases which refers to the distribution with larger COT values correspond with smaller ER values and larger CTH values. The X-axis refers to the ER, the Y-axis refers to the CTH, and the colormap refers to the COT.
APPENDIX
SOUNDING FIGURES

The vertical temperature structure from sounding files of QD station for the 15 cases is attached here. The sounding files are of 00 UTC and 8 am local time.
REFERENCES


Costantino, L., & Bréon, F. (2013). Aerosol indirect effect on warm clouds over South-East Atlantic, from co-located MODIS and CALIPSO observations. Atmospheric Chemistry and Physics, 13(1), 69–88. https://doi.org/10.5194/acp-13-69-2013


