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Air Pollution and Specific Meteorological Conditions at the Adjacent Areas of Sea Ports

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Abstract: Meteorological conditions and phenomena in coastal areas show specific peculiarities caused, or significantly affected, by sharp changes in heat, moisture, and momentum transfer due to the contrast in land-sea underlying surfaces. These conditions may be conducive to trap and retain pollutants in the lowest layer of the atmosphere or to assist in its cleaning. Sea transport is the cheapest one and ports are portals for world trade, often being a basic prerequisite for the development of various economic sectors in the coastal regions. Shipping vessels engines run on heavy fuel oil which has a high polluting impact, as the SO_2 content of heavy fuel oil is 2700 times higher than in road fuel. Some aspects of the role of meteorological conditions on the dispersion of pollutants and the air quality in the biggest Bulgarian coastal cities of Varna and Burgas are subject of discussion in the present paper.

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Keywords: Air pollution, Coastal meteorology, Port areas, European and national legislation

1. INTRODUCTION

The atmospheric boundary layer (ABL) is the lowest layer of the atmosphere which is most directly influenced by the presence of the ground. This is also the layer where people live, so it is very important to know, understand and theoretically describe the processes which occur in it, as well as their effect on our lives and on the ecosystems. At coastal areas, the large thermal contrast between the ocean/sea/big lake and the land drives the well-known sea-breeze circulation, resulting in the confluence of air originating over the ocean with air originating over the land. The contrasts are bigger in sunny summer days under weak pressure gradients and thus the circulation is most pronounced in the sea breeze during the day bringing cooler marine air over the land. The sea breeze is associated with many processes that contribute to the recirculation and trapping of pollution, such as internal boundary layers development, evolution of precipitating convective storms, the creation of strong nearshore thermal, moisture and aerosol gradients, and the formation and transport of fog and low clouds in the coastal zone. The orography of the region also plays significant role in the formation of specific meteorological phenomena in these areas.

Ports could be classified as hubs of world trade and economic activities but they are also major source of ship pollution, vehicle emissions, dust and noise. Most often they are situated close to populated urban areas, which can mean that the inhabitants in these cities are exposed to additional pollution. Major air pollutants generated by port activities include carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxides (NOx), sulfur oxides (SOx) and particulate matter (PM). The health effects of prolonged exposure to these compounds include respiratory and cardiovascular diseases, lung cancer, etc. (Thongplang, 2017).

Shipping emissions are currently increasing and will most likely continue to do so in the future due to the increase of trade on global-scale. Recent study (Viana et al., 2014) shows that in European coastal areas, shipping emissions contribute with 1 -7% of ambient air PM10 levels, 1 -14% of PM2.5, and at least 11% of PM1. Contributions from shipping to ambient NO_2 levels range between 7 and 24%. Impacts from shipping emissions on SO_2 concentrations were also reported in some countries. Shipping emissions impact not only the levels and composition of particulate and gaseous pollutants, but may also enhance new particle formation processes in urban areas.

In order to assess and manage the exposure of people living in the adjacent areas of sea ports, as well as the effects on the environment in these zones, a complex and combined study of the meteorological factors driving the transport and diffusion of pollutants and knowledge of pollution caused by shipping activities are required. This could be achieved by air quality (AQ) monitoring in areas directly surrounding port operations and in a network of stations at some distances around the port. It is also required to have measurements of main meteorological parameters, if possible at the same sites or close to them, where AQ monitoring is done. Providing such type of continuous data can be helpful to identify weather types of days with elevated levels of port generated pollution. A following step then can be to manage the port emissions, reducing them when meteorological conditions are not favorable for dispersion.

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Models are another modern and powerful tool. The progress and improvement of computer technologies during last decades has allowed the development of more sophisticated models or systems of models for air quality assessment and forecasting. Such models can describe the complex coastal meteorology to some extend if run on high spatial resolution. However, the dispersion modeling cannot account for all the factors influencing the quality of the ambient air, and its results in most cases will underestimate the actual situation. In order to test and improve models, as well as to ensure their reliability, it is necessary to verify them against data from observations.

As the national and local environmental agencies aim to improve air quality, ports are becoming a target for air pollution control measures and national and international legislation.

This paper aims giving a short overview of the present state of the art in Bulgaria concerning studies on coastal meteorology and assessment of air pollution. While the influence of weather conditions on the dispersion of pollutants at the Bulgarian Black Sea coast has been relatively well investigated, studying and assessing the impact of ports and port activities on air quality in the adjacent areas and cities are just making their first steps. We suggest some measures to be taken in the near future to deepen such studies in Bulgaria through improved monitoring in coastal regions and adjacent to ports areas.

2. METEOROLOGICAL CONDITIONS CAUSING HIGH POLLUTION LEVELS IN COASTAL AREAS

The level of atmospheric pollution with harmful substances is determined both by their emissions and by the dispersion processes in the atmosphere. The atmosphere is self-purifying in most cases, but in coastal areas the conditions are more complicated.

The main unfavorable meteorological conditions, prerequisite for the accumulation of pollutants in the surface layer of the atmosphere are: low wind speeds (less than 1.5 ms^{-1}) and stable stratification (weak turbulence and so weak vertical mixing). In coastal areas during summer when sea breeze circulation develops, before the onset of the sea breeze in the morning a period of calm weather is observed with duration of 1-2 hours. Similarly, at the transition from sea to land breeze in the evening a period of calm weather is observed. The wind speed of the land breeze during the night is smaller than the wind speed of the sea breeze during the day. So, during nights and transition periods the meteorological conditions in coastal areas are not favorable for pollution dispersion. During the day, the wind speed of sea breeze is higher, but the transformation of the cool marine air over the heated land leads to internal boundary-layer formation (Batchvarova et al, 1999 and Gryning and Batchvarova, 1990). This layer is growing with the distance from the coast and is limited by capping inversion as the convective atmospheric boundary layer over land. Thus, the shallow internal boundary layer keeps the pollution near the ground, although the weather feels good with sunshine and cooling breeze. The air pollution problems in coastal cities are often related to internal boundary layers as reported for Athens (Batchvarova and Gryning, 1998) and Vancouver (Batchvarova et al. 1999).

The atmospheric humidity is a parameter that affects the spread of dust pollutants and plays a significant role in the formation of acidic aerosols. Higher humidity due to the vicinity of seas or lakes is a factor for hydration of pollutants and consequent formation of new toxic compounds.

Another important factor that contributes for poor air quality is topography, which may block the way of polluted air masses and so may lead to high concentrations. Similarly, densely built urban areas may block the ventilation and keep polluted air near the ground.

In coastal areas when the emission is released within the internal boundary layer, a phenomenon called fumigation occurs and again leads to high pollution levels (Luhar and Sawford, 1996).

Improved understanding of meteorological processes in the coastal zone is based on detailed knowledge of marine and terrestrial boundary layers and air-land-sea-interaction, considering both local and large-scale atmospheric dynamics. The application of such knowledge is important for the prediction of sea state and pollutant dispersal.

3. CHARACTERISTICS OF MAIN POLLUTANTS GENERATED BY SHIPS AND PORT ACTIVITIES

Sulphur Oxides (SO_x) emissions can be transported at long distances by the wind. That is how coastal and even hinterland regions get polluted by emissions from shipping and port activities. When SO and SO_2 are oxidised in SO_4, they form sulphate aerosols which are small enough that they could be classified to the group of Particulate Matter (PM). The SO_2 content in heavy fuel oil used by ship engines is 2700 times higher than in road fuel. The European Air Quality Directive 2008/50/EC sets some limits for this pollutant. The 1-hour limit for sulphur dioxide is 350 $\mu g/m^3$ which may not be exceeded more than 24 times per year. The daily limit of 125$\mu g/m^3$ may not be exceeded more than three times per year.

Nitrogen Oxides (NO_x) arise during fuel combustion in the engines of ships, construction machinery, locomotives and trucks. Increasing combustion time and temperature leads to the rise of NO_x emissions. The Air Quality Directive 2008/50/EC sets European-wide limits - 1-hour limit for NO_2 of 200 $\mu g/m^3$ which may not be exceeded more than 18 times per year. The limit per year is a daily average of 40 $\mu g/m^3$.

Particulate Matter (PM) are very small particles and depending on their size are classified as PM10, PM2.5 or PM0.1 with diameter of less than 10 μm, 2.5 μm or 0.1 μm respectively (the last are also called Ultra Fine Particles (UFP)). There is a natural concentration of PM in the atmosphere that consists of aerosol components like dust, marine salt or polls but it is enhanced by diverse anthropogenic effects like the burning of fuels or handling of goods. Especially the combustion of diesel and heavy fuel oil leads to a comparatively high amount of PM emissions. PM also develops when certain pollutants meet other substances and form "secondary particulate matter" (SPM). The smaller the particles are, the worse they affect human health. When it comes to legislation and limits the EU-Air Quality Directive sets for PM10 an average annual value limited to 40 µg/m³ and the daily average value of 50 µg/m³ may not be exceeded on more than 35 days per year. From 2015 there is a limit for PM2.5, too: annual value of 25 µg/m^3. (Project: Clean air in ports, 2014).

Bulgarian legislation is in compliance with the European directives for all of the above mentioned pollutants.

The new EU satellite program aims at tracking polluted air and can become a powerful tool to monitor emissions from shipping. The Sentinel-5P satellite was launched by ESA in October 2017. An image from February 20, 2018 reveals the trail of nitrogen dioxide left in the air as ships move in and out of the Mediterranean Sea. The route that the vessels use to navigate the Strait of Gibraltar is easily distinguished by Sentinel-5P's Tropomi instrument, Fig. 1.

The satellite information could and should be used in monitoring the AQ in ports and the adjacent areas.

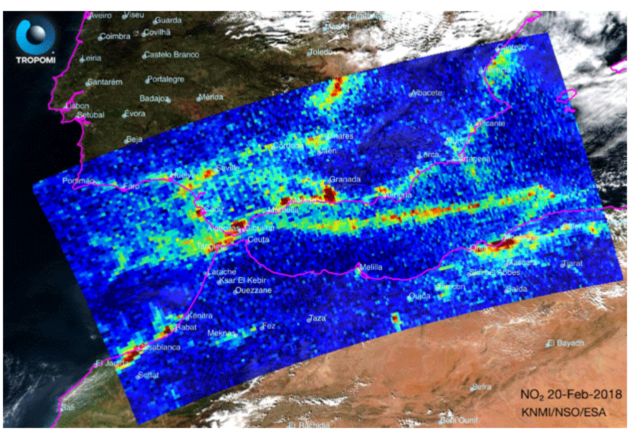

Fig. 1. The trail of nitrogen dioxide left in the air as ships move in and out of the Mediterranean Sea by Sentinel-5P's Tropomi instrument, http://www.bbc.com/news/science-environment-43926232

A study of sulphur dioxide and nitrogen oxides from international shipping in the Baltic Sea, North Sea, north - eastern Atlantic, the Mediterranean, and the Black Sea (Entec(2002), UN ECE (2002)) reveals that while pollutant emissions from land-based sources are gradually coming down, those from shipping show a continuous increase (Fig. 2). This fact implies the need to carry out detailed studies (source and meteorological information, monitoring, modelling, etc.) at coastal areas.

Even though shipping contributes significantly to the international transportation sector, its emissions are not well quantified and are one of the least regulated anthropogenic sources.

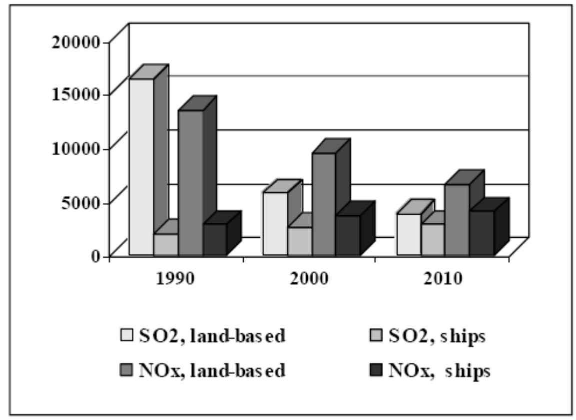

Fig. 2. Comparison of SO_2 and NO_x emissions from land-based sources and ships, ktons. (N. Kozarev et al, 2014)

4. AIR QUALITY IN THE CITY OF BURGAS

The city of Burgas is the fourth largest town in Bulgaria, with about 200 000 inhabitants (in 2012) and an important industrial, commercial, transport, tourism and administrative center. It is built on a complex coastline in a large and deep bay, with three big lakes that bring additional complexity to the terrain and meteorological conditions. The largest refinery on the Balkan Peninsula, Lukoil, is situated to the west, close to the city. The port of Burgas with an oil terminal forms the biggest Bulgarian industrial port area with 59% of the country's imports and exports. At the two terminals of the port are processed mainly general cargoes: metals, wood, grain, food, scrap, machines, etc. Bulk cargoes, such as coal, sugar, salt, ammonium nitrate, etc., are also often processed. The total open storage area of both terminals is almost 240,000 m^2.

The air quality of the city is defined by the emissions due to the operation of the refinery, several power plants and industrial sites, the port and the road traffic, from one side, and by the meteorological conditions from the other.

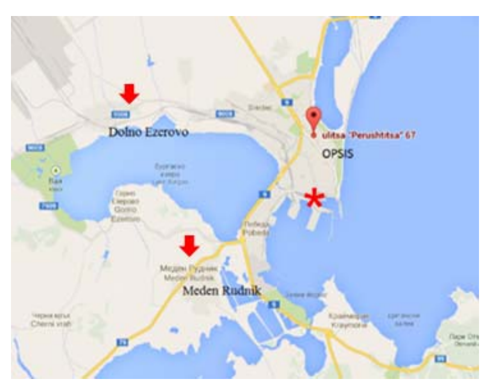

Fig. 3. Monitoring sites: star- port station; pointer – central REA station; arrows – Meden Rudnik (MR) and Dolno Ezerovo (DE).

Within the frame of TEN ECOPORT project, a team from NIMH assessed the impact of Burgas port activities on the AQ during different seasons with regard to PM10 (Batchvarova et al, 2015), using AERMOD atmospheric dispersion modeling system (User guide, 2018). The monitoring was realized by an automatic measuring station (AMS) specially set in exploitation in the port area. It is located in the area of an existing ship repair enterprise and storage of stocks of Bulgarian Ports Infrastructure Company and is representative for the impact of the old and new bulk cargo terminals in northwest direction. At three points in the city there are AMSs of the Regional environmental agency (REA) equipped according to all European requirements and standards in order to submit accurate data to the European Environmental Agency (EEA). The places of the monitoring stations are shown in Fig. 3. The stations DE and MR are considered as urban background accounting also for emissions from the domestic sector and some industrial activities. The central REA station is mainly transport oriented.

Comparing the observed monthly mean PM10 concentrations from the four monitoring stations for the period January – September 2013 reveals distinct seasonal minimum in summer and maximum in winter months at all stations, as well as weaker seasonal variability at the port station. The maximal monthly concentrations at all stations are observed in January, and from those highest is the level at Dolno Ezerovo (DE), followed by the Port, Meden Rudnik (MR) and the station in the centre (REA). Similar monthly distributions are also observed in 2014, 2015 and 2016, suggesting similar processes that determine the observed values.

In winter, in accordance with the predominant western winds, the diurnal mean PM10 concentrations at all stations show close values and variations, suggesting that the Port is in the same air mass as the city. In spring and autumn, the PM10 concentrations at the Port are higher, pointing out that local conditions are more important and a shallow internal boundary layer that forms over land at sea breeze keeps the pollution close to the surface at the port area. Further inland, the height of the internal boundary layer increases and the pollutants are faster diluted.

The AERMOD results for an open source of PM10 (e.g. coal) situated in the port area with arbitrary emission of 10^{-4} $gs^{-1}m^{-2}$ showed higher pollution at all stations in the city when the wind comes from south. In this case the model results were close to the observed concentrations (Batchvarova et al, 2015).

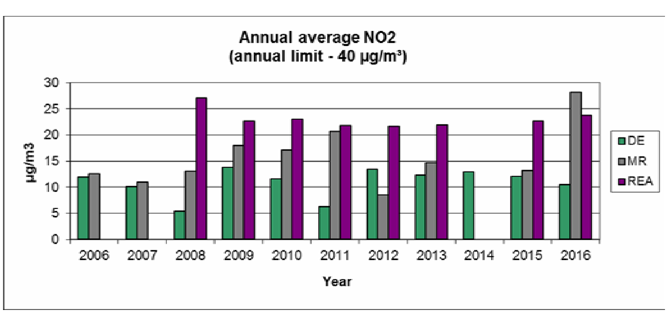

Fig. 4. Evolution of mean annual NO_2 concentration (Source: Annual reports on the state of the environment for Burgas municipality from 2008 to 2016)

The evolution of mean annual concentrations of NO_2 observed in the 3 AMSs is presented on Fig. 4 for the period 2006-2016. The values are less than the annual limit of 40 $\mu g/m^3$ for all monitoring stations.

Within another project, SAAP4FUTURE, the same team from NIMH studied and obtained air pollution maps based on a modern air quality modeling system (Syrakov et al., 2013 a,b) for surface concentrations of major pollutants (ozone, nitrogen oxides, sulfur dioxide and particulate matter) and sulfur and nitrogen deposition for selected specific periods in 2014. Comparison between observed and modelled values of the mean maximal hourly concentrations of NO_2 in the 3 stations in February and June 2014 are shown on Fig. 5 (Georgieva et al., 2015).

In the prevailing part of the region the percentage of deposited sulphates from transboundary sources is above 60 %. Only in the vicinity of Burgas the impact of the local and transboundary sources is similar (~50%).

It is concluded, both from observations and modeling that most often the meteorological situation is favorable and the Port of Burgas does not affect the air quality in the city center.

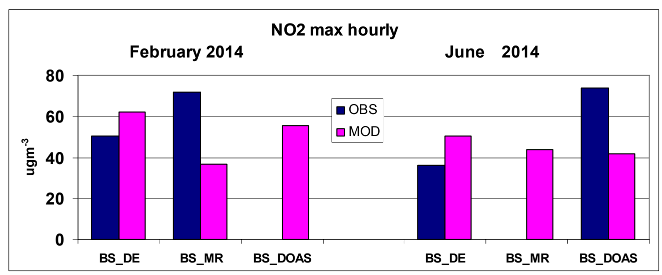

Fig. 5. Modelled and observed NO_2 hourly max concentrations for February and June 2014

To our knowledge, no studies of the impact of port activities on the AQ in the city and adjacent port areas with regard to SO_2 and NO_2 pollution have been made.

5. AIR QUALITY IN THE CITY OF VARNA

The city of Varna is situated in the North-Eastern part of Bulgarian Black Sea shore. Varna is the third largest city in Bulgaria with about 330 000 inhabitants. Situated in the Gulf of Varna, the city is a major economic, cultural and tourist center. The coast is mainly tall and steep, formed by the sea abrasion. Port of Varna is the largest seaport complex in Bulgaria, located on Varna Bay, along Lake Varna and Lake Beloslav. Varna East port is situated deep into the Bay of Varna, at only 1 km distance from the city center. It operates with various general and bulk cargoes and edible liquid bulks. The total traffic at this port facility exceeded 4.1 million tons in 2013. The open storage area is 97,600 m^2.

Varna West, located at 30 km west of Varna city, is the most modern port at the northern Black Sea coast of Bulgaria. It is adjacent to the chemical factories of Devnya which enables effective “factory-to-ship” direct handling of goods. The port has modern technologic lines for handling of soda, fertilizers, cement, coal, ores, phosphates, silica and liquid chemicals.

The open storage area is 346,397 m^2. The places of the monitoring stations are shown on Fig. 6. The REA station is considered as urban background, while the central one "Batak" is mainly transport oriented.

The specific climatic and meteorological conditions and the relief of the region significantly influence the distribution of atmospheric pollutants. For the days with measured exceedances of PM10, a study accounting for wind speed and cloud cover pointed out that the main reason for the high values is the secondary suspension of PM under the influence of the winds. This should be emphasized when formulating measures to reduce atmospheric air pollution by PM10 in the region.

Fig. 6. Map of Varna with the port and 2 monitoring stations

According to the results of the dispersion modelling with SELMAGIS, the territory affected by PM10 concentrations above several limits is the site of the ship repair enterprises and the area around them, like Batak (ECOOB, 2011).

The analysis points out also, that during sea-breeze days no midday decrease of pollutants concentrations is observed. On the contrary, in the afternoon, high values remain, leading to higher daily average concentrations, which is in line with the expectations because of internal boundary layer development.

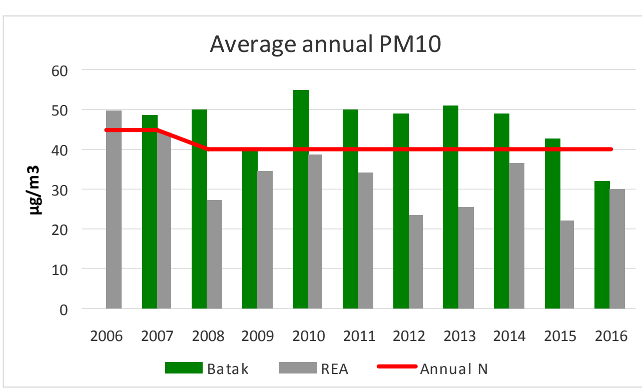

Fig. 7. Evolution of mean annual PM10 concentrations (Annual reports on the state of the environment for Varna municipality from 2007 to 2016)

Fig. 7 shows the evolution of PM10 concentrations over the last 11 years based on the Annual reports on the state of the environment in Varna municipally. It is well seen that for the whole period they are above the limit value of 40 µg/m^3 in the vicinity of Batak monitoring site. Even in 2010, that was with precipitations above the annual norm (but mainly in winter), the PM10 concentration was 1,37 times higher than the annual norm. There were 172 single registered exceedances of the daily limit value of 50 µg/m^3.

The mean annual NO_2 concentrations, based on data from the annual reports on the state of the environment for Varna municipality from 2007 to 2016 (shown on Fig. 8) reveal no exceedances of the AQ norms, except for site Batak in 2016.

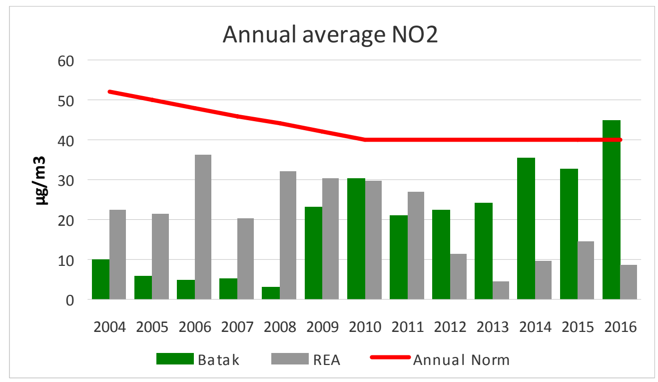

Fig.8. Evolution of mean annual NO_2 concentrations (Annual reports)

It is concluded, both from observations and modeling that most often the meteorological situation and topography of the region of Varna are not favorable for the dispersion of pollutants in the atmosphere, except for strong wind situations.

5. CONCLUSIONS

Reducing port pollution is a top priority for many central and local governments, however it can incur significant cost and is often politically challenging. A number of European projects as APICE (www.apice-project.eu) address these problems and aim at setting good practices for Europe. APICE involves monitoring and studies at main European ports as Barcelona, Marseille, Genoa, Venice and Thessaloniki, emphasizing on the most adverse for human health PM concentrations. In order to improve the quality of the atmospheric air at the Bulgarian coast and adjacent to ports areas, an in-depth analysis of EU air quality standards and following good practices in the preparation of national standards are required. Solving environmental problems in these areas needs complex approach, including: specific AQ monitoring programs in view of breeze circulation and internal boundary-layer formation; modern methodologies and innovative tools such as improved port activities monitoring; advanced data processing systems; and adapted models for air pollutant transport and dispersion. Training and capacity building of port and municipal authorities for developing and implementing effective policies for environmental management of the port areas are also needed.

In order to protect human health and the environment, emissions of harmful air pollutants should be avoided, prevented or reduced according to DIRECTIVE 2008/50/EC on ambient air quality and cleaner air for Europe. To reach this step, improved monitoring programs are needed both for Burgas and Varna and the areas adjacent to their ports, in particular.

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