IR-BASED SATELLITE PRODUCTS FOR THE MONITORING OF ATMOSPHERIC WATER VAPOR OVER THE BLACK SEA

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ABSTRACT. – IR-BASED SATELLITE PRODUCTS FOR THE MONITORING OF ATMOSPHERIC WATER VAPOR OVER THE BLACK SEA. The amount of precipitable water (TPW) in the atmospheric column is one of the important information used weather forecasting. Some of the studies involving the use of TPW relate to issues like lightning warning system in airports, tornadic events, data assimilation in numerical weather prediction models for short-range forecast, TPW associated with intense rain episodes. Most of the available studies on TPW focus on properties and products at global scale, with the drawback that regional characteristics – due to local processes acting as modulating factors - may be lost. For the Black Sea area, studies on the climatological features of atmospheric moisture are available from sparse or not readily available observational databases or from global reanalysis. These studies show that, although a basin of relatively small dimensions, the Black Sea presents features that may significantly impact on the atmospheric circulation and its general characteristics. Satellite observations provide new opportunities for extending the knowledge on this area and for monitoring atmospheric properties at various scales. In particular, observations in infrared (IR) spectrum are suitable for studies on small-scale basins, due to the finer spatial sampling and reliable information in the coastal areas. As a first step toward the characterization of atmospheric moisture over the Black Sea from satellite-based information, we investigate three datasets of IR-based products which contain information on the total amount of moisture and on its vertical distribution, available in the area of interest. The aim is to provide a comparison of these data with regard to main climatological features of moisture in this area and to highlight particular strengths and limits of each of them, which may be helpful in the choice of the most suitable dataset for a certain application.

Keywords: Black Sea, atmospheric moisture, satellite products, cloud fractional coverage, radiosounding measurements.

1. INTRODUCTION

Satellite observations provide new opportunities for monitoring atmospheric properties at various scales over the small-area basins like the Black Sea and for extending the knowledge on the air-sea interface processes. Observations in the microwave (MW) spectrum provide accurate information on atmospheric humidity over ocean, available in both clear and cloudy conditions, but with limited availability close to coastal areas; total precipitable water is the main humidity parameter estimated from these observations. In some cases there are also available vertical profiles of humidity, although with coarse vertical

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resolution. Satellite observations in the infrared (IR) spectrum are available only in clear sky situations, but they allow a better resolution in estimating the vertical distribution of humidity (usually 14-20 levels; up to 100 vertical levels) and they provide reliable information in the coastal areas too. These products may be useful for studies on air-sea exchange processes, planetary boundary layer characteristics, for applications related to marine/coastal short-range forecast, including assimilation into NWP models (e.g. Le Marshall et al, 2006).

In order to select a dataset for a detailed long term analysis it is important to find a compromise between data accuracy and data spatial and temporal coverage optimized for the specific region of the Black Sea basin. Suitable candidates are products developed from IR satellite observations, as they provide a good spatial coverage in both coastal and open-sea areas, satisfactory temporal resolution (e.g. daily) and also a finer vertical sampling than in the case of MW-based products. Analyses at regional scale of such products would facilitate the choice of a certain dataset depending on the specific user-needs and thus extending the use of satellite-derived information.

We address this issue by investigating three datasets of satellite products which contain atmospheric moisture information available over the Black Sea, derived from IR observations. We employ L2 standard products derived from observations provided by AIRS (Atmospheric Infra-Red Sounder), IASI (Infrared Atmospheric Sounding Interferometer), and MODIS (Moderate Resolution Imaging Spectroradiometer). The temporal sampling is generally twice per day, while the spatial horizontal resolution varies from 5km (MODIS), to 25 km (IASI) and 50km (AIRS). Vertical resolution also ranges from 100 pressure levels for IASI, to 14 pressure levels for AIRS and 20 pressure levels for MODIS. The data employed here covers the period September 2008-August 2011.

The analysis focuses on the total precipitable water in the atmospheric column, aiming to characterize the three IR satellite-derived moisture products with regard to climatological features of interest in most applications. The impact of vertical and horizontal resolution of the product on the mean behaviour of analyzed variables as well as the contribution of retrieval algorithm to the differences found between datasets are also considered.

2. DATA AND METHODS

The Level 2 products derived from IR observation of AIRS, IASI and MODIS, for the period September 2008-August 2011, provide the satellite data for this study.

AIRS is a high-resolution infrared spectrometer aboard the Aqua platform, accompanied by the Advanced Microwave Sounding Unit (AMSU) and Humidity Sounder for Brazil (HSB) (Susskind et al, 2003). The L2 product employed in this work is the standard AIRX2RET, version 5, which makes use of IR (from AIRS) and Micro Wave (MW) (from AMSU) radiances. It contains, among other parameters, the profiles of retrieved temperature and water vapor, as well as the integrated water vapor (TPW) and the surface skin-temperature [3]. The horizontal resolution is 45 km and the vertical grid has 14 pressure levels for the moisture variable. The data is freely available from [4].

The IASI Level 2 product used in this work is made available by NOAA (National Oceanic and Atmospheric Administration) [5]. The theoretical basis of IASI retrieval algorithm is similar to that of the AIRS science team algorithm (Susskind et al, 2003), with some differences arising from the different instrument characteristics (NOAA/NESDIS, 2008). The IASI Level 2 product contains profiles of temperature and water vapor as well as the surface skin temperature; it is available in cloudy conditions too, as it includes information in MW spectrum, provided by AMSU. The vertical grid used in the profiles has 100 pressure levels ranging from 1100 hPa to 0.016 hPa. Precipitable water was obtained by integrating the water vapor mixing ratio between surface (1013.95 hPa) and the 200 hPa pressure level.

MODIS is carried onboard the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) Terra and Aqua platforms, being launched in 1999 and 2002 respectively. The MOD07-L2 product (Seeman et al, 2006), based on observations from Terra platform, has a horizontal resolution of 5 km, with 20 levels in the vertical humidity profiles. It is freely available from [8]. The product, available only for clear-sky conditions, includes the integrated water vapor derived from IR observations, the vertical moisture profile and the surface temperature which, for the case of oceanic areas, corresponds to bulk sea surface temperature (SST) (Brown and Minnet, 1999).

The seasonal number of valid profiles over Black Sea in each dataset is shown in Table 1. The selection of valid profiles takes into account the quality flags associated with both TPW and humidity profiles (e.g. in MODIS product), such that ‚best’ and ‚good’ quality data is used. Other selection conditions assure that only coastal and open-sea points are kept in each working dataset, covering the Black Sea and the Azov Sea.

Table 1. ***Seasonal number (x 10^3) of valid profiles over Black Sea in each dataset.***

Season/ Dataset	**DJF**	**MAM**	**JJA**	**SON**
IASI	23.2	36.8	55.4	40.7
AIRS	17.4	28.7	38.8	32.8
MODIS	491.2	924.4	1178.3	1037.6

Additional data on total precipitable water is provided by ERA-INTERIM reanalysis (Dee et al, 2011). ERA-INTERIM is the state-of–the-art reanalysis dataset for the European area and it is widely used in climate modelling. As a gridded dataset (0.75x0.75 deg) with global cover, ERA-INTERIM is suitable for comparisons at basin-scale and it represents a relevant source of additional data for a region with generally scarce data coverage as the Black Sea. TPW from the 12:00UTC reanalysis, as available in ERA-INTERIM archive, was employed in the study, for the period September 2008-August 2011.

Last but not least, information on cloudiness in the Black Sea basin is obtained from the CLAAS dataset (Stengel et al, 2013) based on MSG SEVIRI satellite observations, for the period 2008-2011. The dataset provides, among other parameters, gridded monthly mean values of cloud fractional coverage (CFC) with a spatial resolution of 0.05x0.05 deg., for the MSG full disk area.

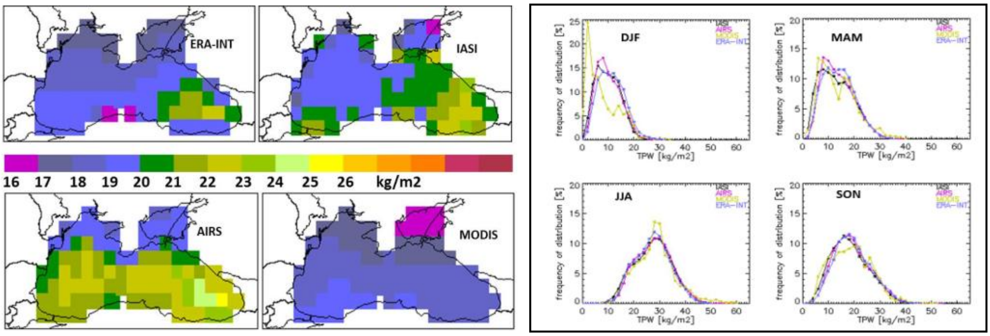
The analysis of all datasets is performed mainly at annual and seasonal time-scales, focusing on the statistical characteristics of values distribution over the basin. In order to analyse the spatial distribution pattern, data from each source has been organized in a regular latitude-longitude grid, on seasonal basis. The grid, with a step of 0.75 degree, is the same as for the reanalysis dataset ERA-INTERIM in order to facilitate the comparison.

3. RESULTS

The annual mean pattern of TPW (Fig.1a) shows for all datasets increasing mean values from North to South, with a maximum located in the SE region. This latter feature is not present in MODIS data, most probably due to unavailability of data in the presence of clouds. A good agreement between the four datasets is found also for the range of annual mean values –between 16 and 24 kg/m2, with smaller upper-limit values in MODIS.

Seasonal probability distribution functions (PDF) of TPW over the entire Black Sea basin is shown in Figure 1b. In winter, MODIS PDF presents a pronounced skewness toward low values. This may be the consequence of MODIS product availability only in clear-sky situations, which forms a class less populated in winter over the Black Sea. In particular for the time interval considered here, the seasonal mean cloud fraction over Black Sea in winter is larger than 70%, (not shown) based on CLAAS dataset. IASI, AIRS and ERA-INTERIM datasets all include cloudy scenes in the corresponding products (e.g. in AIRS, up to 90% cloudiness in the field of view (Susskind et al, 2006). This contributes to a more realistic description of known climatological features in the latter three datasets, by including a larger palette of atmospheric states than IR-only products like the one derived from MODIS.

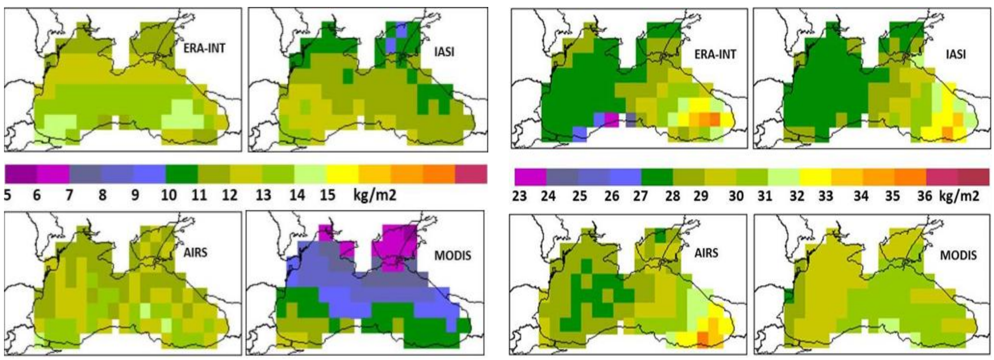
Comparison with ERA-INTERIM dataset for the same period shows a good agreement with IASI and AIRS satellite-derived datasets, in particular during summer and fall. One possible reason for the good agreement between these datasets may be the inclusion of ECMWF forecasted moisture and temperature profiles in the training database used in the derivation algorithm for IASI and AIRS (Susskind et al, 2006). Operational system providing ECMWF forecasts and the one used for ERA-INTERIM have a common core which is reflected in the good match between these datasets. Thus, at basin scale, differences between the PDFs of TPW derived from the three satellite-based datasets are due mainly to instrument characteristics (MODIS available only in clear-sky situations) and to similarities (common elements) in the derivation algorithm (for AIRS and IASI); the horizontal resolution of the products has apparently no contribution to these differences.



(a) **(b)**

Fig. 1. ***(a) Annual mean distribution pattern of TPW for September 2008-August 2011***; ***(b) Seasonal frequency of distribution of TPW for IASI (black line), AIRS (pink line), MODIS (yellow line) and ERA-INTERIM (blue line)***.

The spatial distribution patterns of TPW are shown in Figure 2 for winter and summer seasons. There may be noted features common to all datasets: a north-south gradient during winter, present also in spring and fall (not shown) and an east-west gradient during summer; a maximum of TPW located in the east-southeastern part of the basin, in all seasons. The range of mean values for the period considered, over the entire basin, is quite similar for all datasets, with largest values in summer (between 27 to 36 kg/m^2) and lowest values during winter (between 5 to 15 kg/m2).



(a) **(b)**

Fig. 2. ***Seasonal spatial distribution of TPW for 2008-2011 over the Black Sea basin for: (a) winter; (b) summer.***

The upper limit of seasonal range is generally lower in MODIS dataset, which may be explained by the presence of clouds, especially for the northern basin during winter and south-eastern part during summer. Other differences between the datasets are related to the distribution of seasonal mean values across the basin, as well as to the characteristics (presence, location, intensity) of a secondary maximum in TPW. This is found in ERA dataset in the southwestern sub-basin during winter and, with a smaller intensity, during spring and fall; in MODIS, this feature is more pronounced than in ERA during spring and fall. The presence of this secondary TPW maximum in the southwestern basin may be associated with the cyclonic path, more pronounced in winter (Cordoneanu et al, 1997; Trigo et al, 1999).

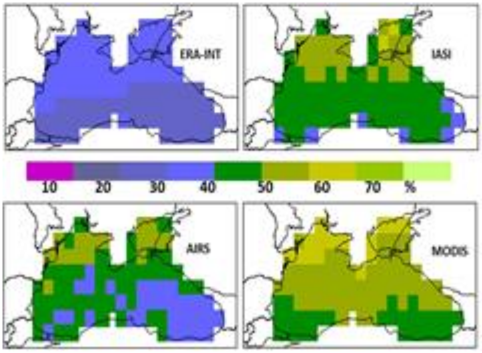


Fig. 3. ***Spatial variability of the ratio (STDEV/MEAN), in %, for winter season.***

The standard deviation (STDEV) associated to the mean seasonal value in each gridpoint shows quite a large variability in a season – e.g. for MODIS, in winter the STDEV represents about 60-70% from the mean (Fig. 3); for AIRS and IASI is little less (40-50 %); for summer, in ERA-INTERIM, AIRS and IASI the ratio STDEV/MEAN is about 20-25%, while in MODIS is in the range 38-43%. This may be the consequence of two factors: a) MODIS, having a higher horizontal resolution, is able to capture horizontal patterns with finer details, thus showing a larger spatial variability; b) in AIRS and IASI, due to MW correction for cloudiness, the atmospheric situations are better sampled, thus a more uniform distribution of values is obtained. Therefore, both the horizontal resolution of the product and the instrument characteristics may have a contribution to the spatial variability of TPW as found in each satellite-based dataset. It should be noted, however, that during the winter, in all datasets, a similar pattern of the ratio STDEV/MEAN is found, with maximum values in the northern part of the basin. This pattern is not apparent in any other season, suggesting a realistic feature of this region associated with higher variability of TPW during winter.

4. CONCLUSIONS

Three datasets containing IR satellite-derived information on atmospheric moisture have been analyzed with respect to seasonal characteristics of total precipitable water over Black Sea, for the period September 2008-August 2011. These data were compared with ERA-INTERIM reanalysis for the same period. The results show known climatological characteristics of TPW, in good agreement with other studies referring to Black Sea region (e.g. Zveryaev et al, 2008) and highlight particular features of this basin. Some characteristics of satellite-based data are also identified as influencing the results.

General climatological features of TPW spatial distribution in the Black Sea basin are present in all satellite-based datasets: a North-South increase of mean

TPW in all seasons except for summer, when a West-East gradient prevails; a maximum mean TPW located in South-Eastern basin during whole year; a secondary maximum in South-Western area, more pronounced in winter and probably associated with the cyclonic path. Differences between the analyzed datasets are related to the range of mean values over the basin, the lowest values being found in MODIS product.

Seasonal variability of TPW is largest during winter. For this season, a similar pattern of the ratio STDEV/MEAN is found in all datasets, with maximum values in the northern part of the basin. This pattern is not present in any other season, indicating a realistic feature of this region associated with higher variability of TPW during winter.

Some of the differences and similarities between datasets may be partially explained by the specifics of satellite-derived geophysical data. In particular, the influence of instrument characteristics or of the derivation algorithm on the mean features of TPW is more evident in two aspects: a) under-sampling of atmospheric situations in MODIS dataset due to the unavailability of observations in cloudy condition, as shown by the winter PDF skewed toward low values and in general by lower mean values; b) similarities between IASI, AIRS and ERA-INTERIM datasets, due to common elements in the derivation algorithm and/or operational system. The spatial sampling, which is different in each satellite-based dataset, has a quite low impact on the seasonal mean behavior of TPW. As expected, if the data is resampled in a coarser grid (e.g. that of ERA-INTERIM, as used here), differences between satellite-derived datasets become negligible and statistics of satellite-derived data are similar to ERA-INTERIM data. These findings may give helpful hints for selecting a satellite-derived moisture dataset for specific applications.

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