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Spatial and seasonal patterns of diurnal differences in ERS Scatterometer soil moisture data in the Volta Basin, West Africa

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Abstract Soil moisture is the key variable in the hydrological cycle. In the Volta Basin, West Africa, where rainfed agriculture forms the main source of income for the majority of the population; productivity relies on available soil moisture or “green water”. Progress will depend on good management of green water, and will be strongly based on monitoring results. Data scarcity in the Volta Basin emphasizes the necessity for remotely sensed soil moisture estimates that allow for more stable monitoring techniques. New soil moisture satellites such as SMOS and MetOp provide improved technical means for soil moisture monitoring. In preparation for these new sensors, historical ERS Scatterometer data over the Volta Basin provided by the Global Soil Moisture Archive have been analysed. The basin area is subject to a natural 1000 km long moisture gradient from the southern tropical rain forest to the northern Sahelian grass savanna. The soil moisture fields generated from ERS Scatterometer data reflect the spatial and temporal climatic patterns well. Our study investigated a weak but consistent anomaly between the backscatter measurements acquired during morning and evening overpasses. Maps generated from the difference between morning and evening overpass data reveal spatial and seasonal patterns that differ from the moisture gradient driven by the local climatology. The observed diurnal differences are in some regions, in particular in the central and forested savanna areas of the Volta basin, in the order of 1 dB, or even somewhat higher. In addition the detected patterns shift temporally in accordance with the transition from wet to dry seasons. Regional and seasonal deviations from the natural moisture gradient are identified and possible explanations examined. It appears that water stress causes diurnal changes in forest canopy water content resulting in somewhat lower backscatter during evening than during the morning acquisitions, but other explanations such as azimuthal effects cannot yet be excluded.

Key words remote sensing; soil moisture; West Africa

INTRODUCTION

Available soil water is the key link between the land surface and the atmosphere. Large-scale climatic feedback mechanisms are highly dependent on available soil water. Climate change studies over both Europe (Seneviratne *et al*., 2006) and West Africa (Koster *et al.*, 2004) show an increasing importance of reliable soil moisture estimates for modelling and prediction.

In West Africa, with its moisture limited environment, rainfed agriculture forms the main source of income for the majority of the population. Agricultural productivity in Western Africa is highly dependent on available soil moisture or “green water” (Rockström & Falkenmark, 2000). In order to improve agricultural productivity in these regions we need reliable prediction tools based on reliable hydrological and climatological models, and improved observations from *in situ* networks and satellite constellations. Remote sensing of soil moisture is a difficult problem due to the interference of other parameters such as vegetation or surface roughness on the satellite signal. But due to recent advances in both satellite technology and retrieval algorithms, more and higher-quality satellite soil moisture data sets will become increasingly available (Kerr, 2007; Wagner *et al*., 2007).

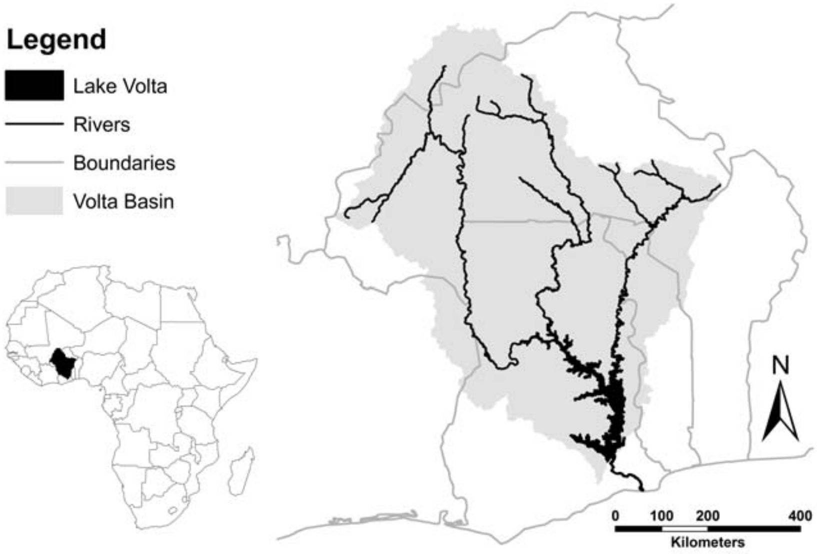

Fig. 1 The Volta Basin, West Africa.

New soil moisture sensors onboard EUMETSAT’s MetOp and ESA’s SMOS missions have the potential to significantly improve current soil moisture estimates. In preparation of these new data we analysed 10 years of ERS Scatterometer data over the Volta Basin, West Africa (Fig. 1). Soil moisture data extracted from the Global Soil Moisture Archive (Scipal *et al*., 2002) showed patterns in agreement with climatic gradients. However, diurnal differences in soil moisture between morning and evening passes were observed which were not expected. An analysis of the pre-processed backscatter data confirmed that there are diurnal differences between 10:00 h and 22:00 h overpass data in the order of up to 1–2 dB. The detected patterns were not in accordance with the natural moisture patterns found in the Volta Basin. The objective of this study has therefore been to investigate the potential reasons for these diurnal patterns. In the following sections the study region, its climate and vegetation, are presented, followed by a methodological description of the data processing. Then the results are presented, followed by a discussion, and the conclusions.

The Volta Basin

The study area (6°W–3°E, 4–15°N) covers the Volta Basin that is located in the central part of West Africa (see Fig. 1). The regional climate causes a high to low moisture gradient from south to north. This moisture gradient determines the vegetation that ranges from tropical rainforests at the coast to Sahelian savanna in the north (for more information, please see the GLC 2000 land cover map, Mayaux *et al*., 2006). Elevation in this region is generally flat with only few exceptions, such as the mountainous regions along the southern boundary of the Volta Basin (http://srtm.usgs.gov/).

The West African climate is organized along a longitudinal axis with high annual precipitation in the south and low annual precipitation in the north. Intra-annually, the climate is divided into wet and dry seasons. The amount of rainfall and the length of the wet season is determined by the movement of the Intertropical Convergence Zone (ITCZ). From south to north, the wet season becomes shorter, which causes longer dry periods and less evenly distributed available moisture over the year. Annual precipitation ranges from 2000 mm year^{-1} at the coast to 500 mm year^{-1} in the north. The wet season length varies from nine to three months, and changes from a bi-modal distribution in the south to a mono-modal distribution in the north (Hayward & Oguntoyinbo, 1987). In Fig. 2, the distribution and zonality of precipitation, based on CRU climate data, is depicted (New *et al*., 2002).

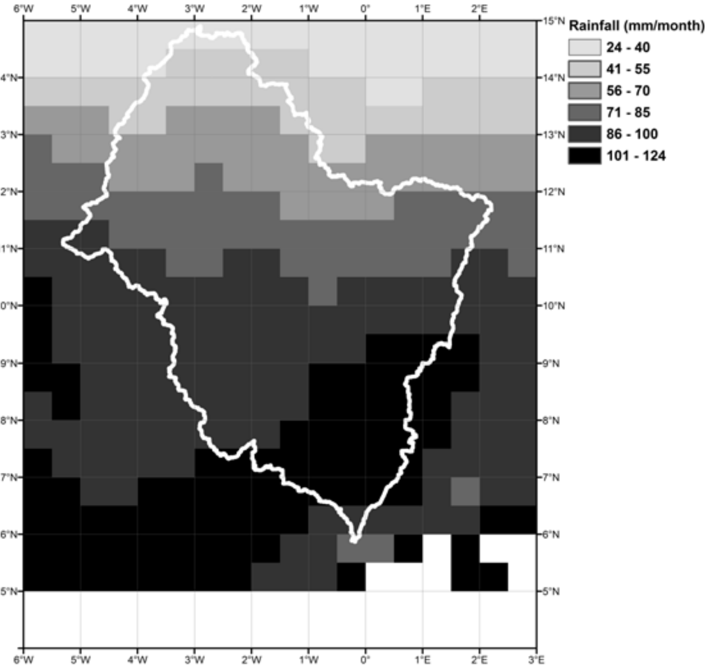

Fig. 2 Average CRU precipitation (1992–2000).

Land cover in the region is controlled by climate, available moisture, population density, geology, and soil properties. Southern West Africa has high, evenly distributed moisture availability throughout the year that results in dense vegetation cover. Natural vegetation in the south is classified as rain forest and guinea forest. Towards the central and northern parts of the study region, moisture content decreases and is not constant over the year. The vegetation cover here is classified as savanna. The savanna is again sub-divided into several types that are mainly dependent on tree density: forest savanna, open woodland savanna, and shrub savanna. A detailed vegetation map for the study region has been developed by the GLC 2000 project (Mayaux *et al*., 2006).

Despite the natural conditions that determine vegetation classes, population density and agriculture also influence their distribution and extent. Agricultural areas throughout the study region generally consist of small plots and are highly heterogeneous, often interspersed with trees and shrubs. Rainfed agriculture is the main source of economic income in West Africa. High population density therefore results in extensive land conversion and deforestation.

METHODOLOGY

The satellite soil moisture data used in this study are taken from the Global Soil Moisture Archive located at http://www.ipf.tuwien.ac.at/radar/index.php?go=ascat (Scipal *et al.*, 2002). For soil moisture information scatterometers on board of the European Remote Sensing Satellites ERS-1 and ERS-2 by the European Space Agency are used. The ERS scatterometers operate at a 5.3GHz (C band) vertical polarization. Backscatter measurements are collected under different incidence angles ranging from 18° to 57° using three sideways looking antennas. Each antenna beam provides backscatter measurements for 50 km resolution cells with a grid spacing of 25 km. The overpass frequency of each grid point varies between two and ten days, and overpass times are at approximately 10:30 h (descending) and 22:30 h (ascending). All backscatter measurements are processed towards and incidence angle of 40° (Wagner *et al.*, 1999).

The processed ERS Scatterometer data from the Global Soil Moisture Archive is used to compute the diurnal differences between different ERS overpass times. The analysis is done on backscatter (dB) data from 1992 to 2000 (Fig. 3). The year 1993 has been excluded from the computation, because 1993 shows an imbalance in overpass frequency with less night overpasses. Including 1993 data, however, does not have a significant effect on the pattern distribution.

Diurnal differences are computed from backscatter data of day and night overpasses from the Volta Basin according to equation (1).

$$\Delta\sigma^0 = \frac{1}{N}\sum_{n=1}^{N}\sigma^0\left(40\right)_{n,morning} - \frac{1}{M}\sum_{m=1}^{M}\sigma^0\left(40\right)_{m,evening} \qquad (1)$$

where $\sigma^0(40)$ is the backscattering coefficient at 40° incidence angle expressed in decibels, and N and M are the numbers of *morning* and *evening* overpasses for the selected time slice. In the following, overpasses around 10.30 h and 22.30 h are referred to as morning and evening overpasses. For each pixel the day and night

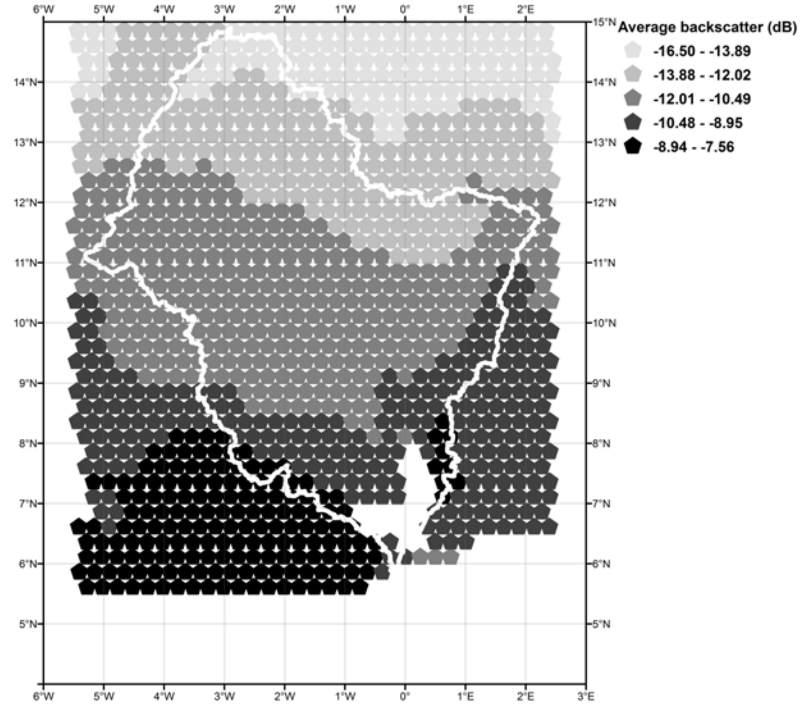

Fig. 3 Average ERS Scatterometer backscatter (1992–2000).

backscatter data is averaged over different time slices: long term (1992–2000), hydrological years, and monthly averages. The mapped diurnal patterns are shown in absolute backscatter (dB) differences between the night and day averages.

RESULTS

Soil moisture distribution over the Volta Basin as depicted by the ERS scatterometer shows a clear north–south gradient that corresponds well with both rainfall and vegetation. However, absolute differences between morning and evening overpasses show different patterns that do not follow the natural moisture gradient (see Fig. 4). In reference to the local conditions we identified four regions: the southwestern tropical forest (I), the central Volta Basin (II), the Niger wetlands in the Northwest (III), and the northern part of the Volta Basin (IV). The four regions can be linked to different types of vegetation, vegetation density, and levels of available water. Region (I) in the tropical forest has a high vegetation cover with relatively dense canopy cover and a high level of available water. High annual precipitation and evenly distributed water availability throughout the year result in uniform moisture content of both soil and vegetation.

Region (II), the central Volta Basin, and region (III), the Niger wetlands, are subject to less annual precipitation and long dry season periods. The vegetation, as can be seen in the tree density map (see Fig. 5), shows high tree densities as compared to the surrounding area. Towards the end of the wet season and the beginning of the dry season vegetation in both regions is under severe water stress. Grasses and small

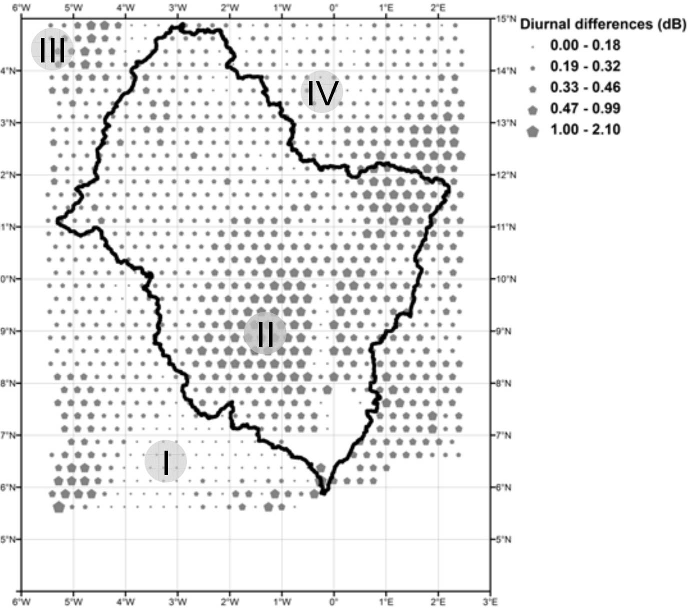

Fig. 4 Average diurnal backscatter differences (1992–2000, without 1993).

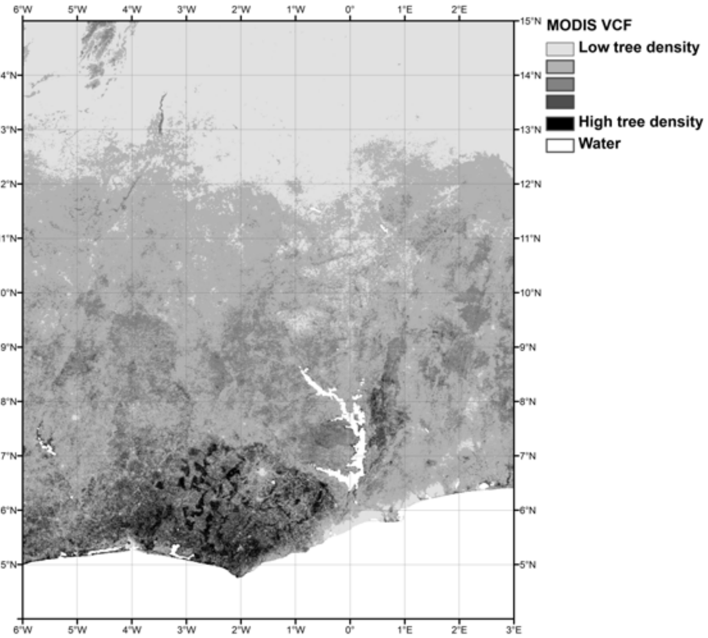

Fig. 5 MODIS VCF tree density map.

shrubs disappear and only woody vegetation lasts through the dry season. Region (IV) has a similar moisture regime as regions II and III but the general vegetation cover is different. The vegetation consists only of shrubs and grasses and moisture is limited. Due to the low tree cover, the vegetation almost entirely disappears during the dry season.

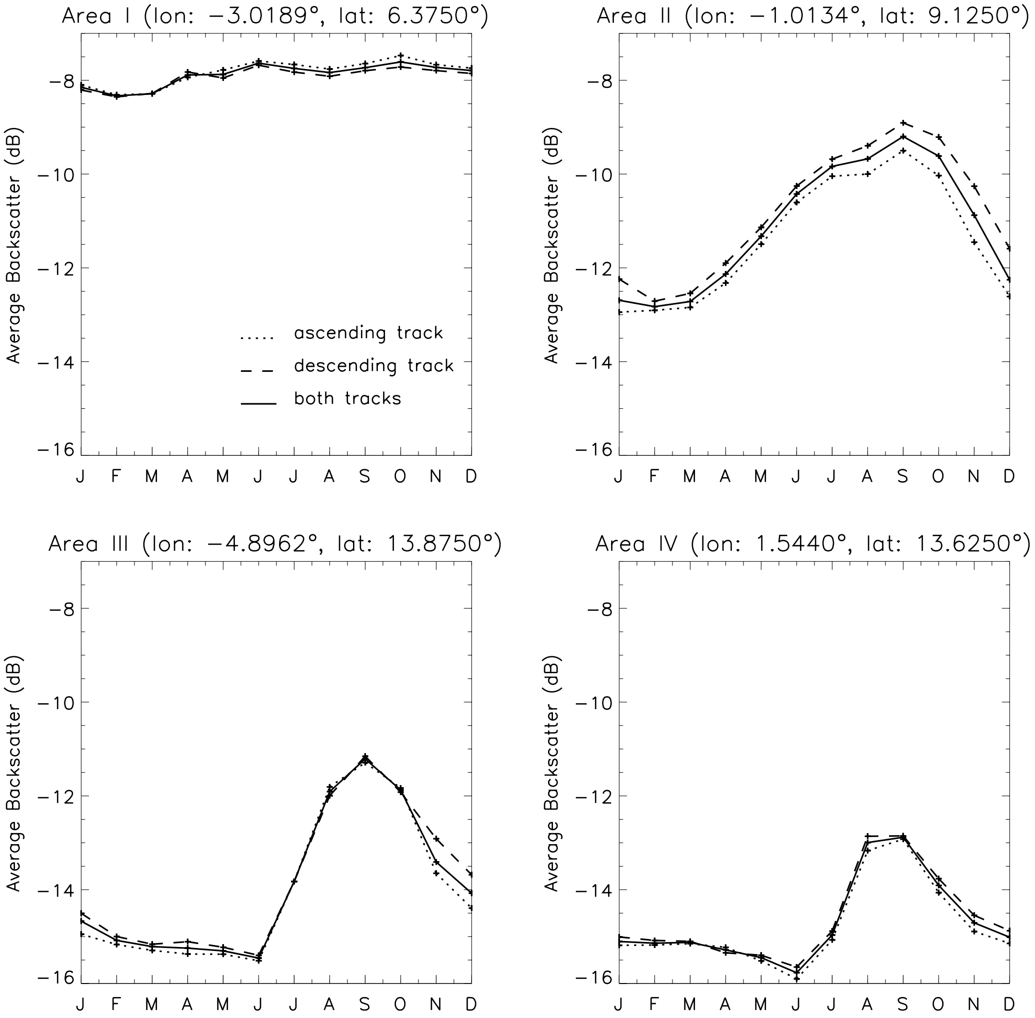

Fig. 6 Monthly backscatter differences for single pixels within the four identified regions. Morning overpasses correspond to the descending and evening overpasses to the ascending track.

The identified patterns emerge in multi-annual averages (see Fig. 4), as well as in monthly averages. Figure 6 highlights single pixels within the four identified regions. The monthly distribution of diurnal differences for regions (II) and (III) show that backscatter differences are highest between the end of the wet season (October) and the mid dry season (January). Note that, overall, the effect is quite small compared to the variations due to soil moisture and seasonal growth of vegetation.

DISCUSSION AND CONCLUSIONS

Region (I) shows low diurnal differences in backscatter. This region is homogenously covered by forest and has high moisture availability throughout the year. Region (II) shows the highest diurnal differences and is covered by a mixture of trees and grasses.

Region (III) is the internal delta of the Niger, which is subject to extensive flooding from July to October. Region (III) shows high diurnal differences in backscatter, especially during the flood recession. Region (IV) has low diurnal differences, comparable to those of Region (I), but is uniformly vegetated by grasses.

We see spatial patterns in the diurnal differences that do not follow the overall moisture and rainfall gradients. The diurnal differences seem to reflect large scale patterns that need to be explained physically. For a given look-angle, backscatter is determined by the geometry of the surface and its dielectric properties. Diurnal variations in both geometry and dielectric properties may give cause to the observed patterns. We consider the following possible explanations: (a) diurnal variations in vegetation water content; (b) diurnal variation in water stored on leaves and topsoil due to regular diurnal patterns of rainfall, (c) diurnal variations in the surface soil moisture content due to diurnal variations in evaporation and water recharge from the profile; (d) azimuthal anisotropy; and (e) differences in Bragg scatter from open water caused by variations in wind in Region (IV).

(a) Diurnal variations in vegetation water content have been observed in trees (Slatyer, 1967; Gates, 1991; Way *et al*., 1991). Water stored in leaves, branches, and trunk are depleted over the course of the day through transpiration. During the night, this water is recharged from the soil until it reaches its maximum before sunrise. Depending on soil water availability and atmospheric demand, full recharge and depletion may be reached at different times of the day. When soil water is limiting, such as during the beginning of the dry season, recharge may not yet be complete during the early evening hours. These diurnal patterns in tree water content are likely to result in diurnal fluctuations of the dielectric properties. It is interesting to note that the region with the largest diurnal variation in backscatter is Region (II) where we find trees that are subject to limiting soil moisture.

(b) Variation in water stored on leaves and topsoil may also be diurnal. Rain may fall preferentially during the night, leaving water on the surface during the morning overpass. Also dew would be more prominent during the morning than during the evening. Even when rainfall is distributed evenly over the day, evaporation would be much higher between the day and night overpass times than between the night and day overpass times, leading to less water on the surface in the morning. This process would only explain differences in backscatter during the rainy season.

(c) The topsoil moisture content varies over the day due to diurnal differences in evaporation and recharge of the topsoil from deeper layers during the night. This explanation appears unlikely since one would expect all regions to exhibit similar diurnal patterns in the topsoil moisture content, independent of vegetation cover.

(d) Azimuthal anisotropy has been shown to have a distinct effect on backscatter. Morning and Evening passes have different azimuthal look angles and structural features on the ground may, therefore, result in systematically different backscatter (Bartalis *et al.*, 2006). Examples of terrains that have shown pronounced azimuthal effects in the order of 1–5 dB are slopes, urban areas, tillage patterns, regular land use patterns and uniform micro-relief. Even over areas where these effects are not apparent, differences in the order of up to 1 dB can easily be observed.

(e) For region (III), the internal Niger delta, Bragg scatter from open water may be relevant. Bragg scatter is caused by wind, which in West Africa tends to be much higher during the day than during the night. Because Bragg scatter causes a relatively large increase in backscatter, even small areas with open water may cause a higher backscatter during the day.

We have identified differences between morning and evening backscatter measurements over several regions in and around the Volta Basin. Both multi-annual averages as well as monthly averages result in similar regional patterns. The spatio-temporal distribution of these patterns is described here for the first time and is not yet well-understood. Low diurnal differences in backscatter are found in regions with high moisture availability and vegetation cover, or in regions with low vegetation cover. We have postulated five possible mechanisms that may contribute to the observed patterns. Ground-based observations will have to be made to come to definitive conclusions about the cause.

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