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Rainfall Regime Shifts as a Proxy for Hydrological Climate Change Vulnerability

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Abstract: In the context of intensifying global climate change, the hydrological system of moderately continental and arid regions exhibits extreme sensitivity. The atmospheric rainfall regime is used as a key proxy indicator to assess this vulnerability, as the deficit of atmospheric moisture and shifts in precipitation patterns directly threaten regional water resources security. This study aims to quantitatively analyze the long-term shifts in the rainfall regime within Mykolaiv region and determine their direct contribution to escalating hydrological vulnerability. To achieve this goal, a comprehensive environmental monitoring approach was employed, involving the analysis of multi-year meteorological data from 1980 to 2024, supplemented by information from geographical databases (e.g., Google Earth Engine) and official regional environmental reports. Statistical analysis methods were utilized. A detailed analysis was performed on the seasonal redistribution, frequency, and intensity of precipitation. The analysis established that the Mykolaiv region, Ukraine, is characterized by a persistent atmospheric precipitation deficit, with average annual figures critically ranging between 409 and 469 mm. The main climate factors driving hydrological vulnerability are not merely the total quantity, but the significant shifts in the pattern of fallout. Firstly, there is a clear seasonal imbalance, disrupting the region's natural hydrological cycle. Secondly, an increase in intense, short-duration storm events has been recorded. This diminishes the effectiveness of soil moisture penetration and generates rapid surface runoff, paradoxically increasing the risks of both soil drought and flash flooding. Finally, the calculation of the GTC consistently demonstrates the predominance of very dry and moderately dry conditions over many years, unequivocally confirming a clear tendency towards aridification (desertification) in the southern districts. Thus, these quantitative and qualitative changes in the rainfall regime serve as a direct and reliable indicator of the region's increasing hydrological vulnerability. These shifts negatively impact the stability of aquatic ecosystems, notably leading to the shallowness of the Southern Buh River, and necessitate the urgent development of integrated adaptation strategies to enhance water resilience.

Keywords: rainfall regime, hydrological vulnerability, water security, climate factors, sustainable development, environmental monitoring

1. Introduction

Over the twentieth century and into the first quarter of the twenty-first century, climate change has profoundly altered global atmospheric precipitation patterns, emerging as a critical driver of hydrological instability. International assessments confirm that global warming is increasingly manifested through significant shifts in rainfall frequency, intensity, and spatial distribution. These alterations result in a dual crisis of prolonged drought and water scarcity in many regions, simultaneously intensifying the risks of flash floods and soil erosion in others.

This escalating crisis in precipitation regimes, driven by fundamental climate factors, poses significant challenges to achieving the Sustainable Development Goals (SDGs), particularly those related to water (SDG 6: Clean Water and Sanitation) and climate action (SDG 13). Effectively addressing these precipitation-induced changes is essential for ensuring sustainable development and protecting global water resources security for future generations (Akhtar et al. 2021, Arif et al. 2023, Ishchenko et al. 2019, Mitryasova et al. 2016, Pohrebennyk et al. 2016, 2017, Sadhwani & Eldho 2023, UN-Water, 2020, UNESCO, 2020).

Consequently, studying the impact of shifting precipitation dynamics and the resultant hydrological extremes on aquatic ecosystems is paramount for maintaining biodiversity and ecosystem resilience. This environmental monitoring research provides a crucial foundation for developing robust and sustainable water resource management strategies in the face of escalating global environmental changes (Bernatska et al. 2023, Mitryasova et al. 2016, 2018, 2021, Mats et. al. 2025).

Atmospheric moisture is one of the parameters that determines the climatic conditions of the region and serves as a limiting factor. This factor plays a leading role in weather and climate formation. This factor plays a leading role in the formation of weather and climate. Atmospheric moisture and its cycle significantly affect all aspects of the climate system, and form specific characteristics of the climate of the territory (Trenberth & Shea 2005, Findell et al. 2020).

Atmospheric moisture and its cycle (hydrological cycle) is the process of constant movement of water between the oceans, atmosphere, and land. This cycle covers the following main stages: evaporation due to the transition of water from a liquid state to a gaseous state under the influence of solar heat. Water evaporates from the surface of oceans, rivers, lakes, soil, and plants (transpiration); condensation occurs due to the process of converting water vapor into a liquid as it rises into the atmosphere and cools to form clouds and fog. Precipitation occurs when water droplets or ice crystals in the clouds become heavy enough that they fall to the ground in the form of rain, snow, hail, or sleet. Runoff is due to the fact that part of the water that fell in the form of precipitation flows down the surface of the earth into rivers, lakes, and oceans. Some of this water seeps into the soil and replenishes underground aquifers. Return to the ocean due to the fact that rivers and groundwater return water to the ocean, where the cycle begins again (Chahine 1992, Gleick 1996).

Therefore, atmospheric moisture is an integrated indicator and plays an essential role in maintaining climate and weather conditions on Earth. It affects temperature, cloud formation, precipitation, and even the life of plants and animals. We outline some key characteristics of atmospheric moisture that formed the basis for choosing it as a critical climate factor: humidity affects human comfort and health, technological processes, and vegetation, as plants rely on water for photosynthesis and transpiration. Climate change affects humidity and precipitation patterns, altering them due to global climate change and impacting the availability of water resources. So, data on atmospheric moisture and its cycle help in water management, weather forecasting, and understanding global climate change.

For this research, the amount of precipitation was chosen as a fundamental characteristic of atmospheric moisture, which allows for the description of the region's moisture regime. The unit of measurement is the average long-term rainfall for the year or season. Seasonal and annual rainfall are the sum of the daily amount of precipitation for the corresponding period. Precipitation anomalies are the relative values of changes in their amount per year, season, in the modern climatic period relative to the base climatic period.

The Mykolaiv region is characterized by a continental type of precipitation. The main characteristics of the continental type of precipitation are:

The summer months are often characterized by more rainfall, as warm temperatures favor increased evaporation and convection processes that lead to rain. Thunderstorms may occur in some areas.

The winter months, on the other hand, are characterized by less rainfall, often in the form of snow. Due to low temperatures, evaporation decreases, and air humidity decreases (×Mats et al. 2025).

The amount of precipitation due to the fact that the total amount of precipitation in continental areas is usually less than in coastal areas. This is due to the remoteness from large bodies of water, which are the primary sources of moisture.

The distribution of precipitation can be uneven, with sharp periods of rain and dry periods. In summer, there may be short-term but intense rains. An interesting feature is the fact that in winter and spring, there is almost the same amount of precipitation, about 22%. In the autumn, there is a slightly higher amount of precipitation – 32%.

The purpose of the research is to study rainfall regime shifts as a proxy for hydrological climate change vulnerability, influencing the state of water resources on the example of the Mykolaiv region. These territories geographically belong to the Northern Black Sea region.

The object of research is the Mykolaiv region.

Mykolaiv region is located in the south of Ukraine, within the Black Sea lowland. The region occupies the territory in the basin of the lower reaches of the Southern Buh River and is washed by the waters of the Black Sea. The Mykolaiv region has a variety of landscapes: from steppes to forest-steppes, as well as significant water resources (National Report, 2023, 2024).

2. Materials and Methods

The methodological framework was built upon a combination of established research techniques, including systematic observations, comparative analysis, synthesis, and generalization of data. The quantitative core of the study involved mathematical modeling, specifically utilizing regression analysis to identify and project long-term trends in precipitation parameters. Data processing and graphical representation were conducted using Microsoft Excel. The research materials were sourced from authoritative and verifiable data repositories. Primary climate factors, particularly precipitation amounts and regimes, were derived from the results and official records provided by the regional hydrometeorological service. For a comprehensive assessment of the environmental parameters across Mykolaiv Oblast, the study utilized strategic and program databases, including National and Regional Reports (National Report, 2023, 2024; Ukrainian Hydrometeorological Center). Furthermore, the Ventusky resource (Ventusky 2024, UNEP Global Environment Monitoring System) was employed as a robust tool providing accurate, time-series meteorological indicators and changes across the globe and at specific regional points.

3. Results and Discussion

In general, the Mykolaiv region is characterized by high atmospheric temperatures, precipitation deficit, and increased wind speed. Moisture deficiency can begin in April and end in October. During this period, as a rule, about 170 days with high temperatures are observed, which will affect the state of aquatic ecosystems, causing eutrophication phenomena. In the region and the city, precipitation falls, as a rule, in the form of rain and showers, which take place throughout the year (Table 1). It has been determined that heavy rains have the greatest recurrence. It is noted that, on average, there are about 80 days with showers per year, more than 70% of which are observed in spring and summer. May and June are the richest months for showers (over 30%, 13 days). However, precipitation in the form of rain is recorded annually for about 20 days (every 18 days, which is a relatively small amount). Such intensity of rains affects the state of water resources, and also determines the conditions of significant risks for the agricultural sector of the economy.

Table 1. Number of days per month, season, and year with rain and snow in the Mykolaiv region during 1991-2024

Period	Snow	Strong Snow	Wet Snow	Heavy sleet	Shower/ Heavy Rain
January	6.9	3.6	0.6	4.8	2.3
February	5.1	3.1	0.7	4.0	2.4
March	2.6	2.2	1.0	4.9	5.8
April	0	0.2	0.2	3.1	9.2
May	0	0	0	1.1	12.3
June	0	0	0	0.6	12.3
Jule	0	0	0	0.2	7.6
August	0	0	0	0.5	7.6
September	0	0.1	0.1	1.1	6.4
October	0	0.1	0.1	2.9	4.5
November	1.4	1.3	0.6	5.4	2.8
December	4.3	3.2	0.6	5.6	7.4
Winter	**16.3**	**9.7**	**1.9**	**14.4**	**12.1**
Spring	**2.6**	**2.4**	**1.2**	**9.1**	**27.3**
Summer	**0**	**0**	**0**	**1.3**	**27.5**
Autumn	**1.4**	**1.4**	**0.8**	**9.4**	**13.7**
Total in a year	**20.3**	**13.5**	**3.9**	**19.8**	**80.6**

The increase in precipitation in autumn is due to the increase in the amount in September, as evidenced by the diagram of Fig. 1. In general, in the Mykolaiv region, on average, about 120 days with precipitation are determined per year; in other words, every third day of the year is characterized by precipitation.

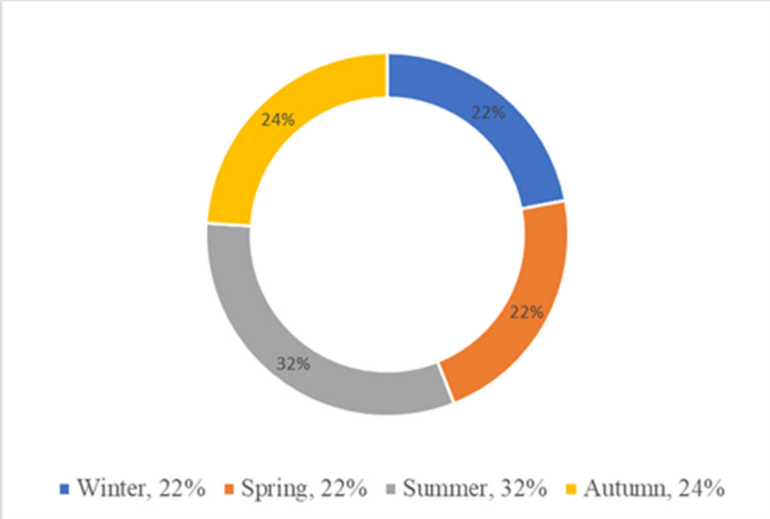

Fig. 1. Amount of precipitation by seasons (%) in Mykolaiv region during 1981-2024

According to long-term observations, the maximum duration of a continuous rainy period can reach a week. The amount of daily precipitation of more than 5 mm is effective for agricultural production and aquatic ecosystems at high air temperatures in summer. On average, such precipitation is observed about 36 days per year, which is 10% of the days of the year and causes critical conditions for agriculture. At the same time, up to three days of precipitation of more than 30 mm per day are observed annually; Once a year, there is precipitation of more than 50 mm per day.

To characterize the moisture supply of the territory, we use the Selyaninov hydrothermal moisture coefficient (GTC) (formula 1) as the ratio of the sum of precipitation during the period when the average daily air temperature is above +10°C to the sum of active temperatures for the same period, reduced by 10 times.

$$GTC = \frac{\sum P}{0.1\sum T} \quad (1)$$

where:
$\sum P$ – the amount of precipitation for a specific period (of course, per month) in millimeters,
$\sum T$ – the sum of the average daily air temperatures for the same period in degrees Celsius.

According to the values of the Selyaninov hydrothermal moisture coefficient (GTC), five types of climate are distinguished:

- very dry (0.4-0.7),
- moderately dry (0.7-1.0),
- moderately humid (1.0-1.2),
- wet (1.2-1.5),
- excessively humid (more than 1.5) (Balabukh & Malytska 2017).

Graph Fig. 2 shows the average monthly precipitation (mm) in the Mykolaiv region for the period from 1981 to 2024. The highest amount of precipitation is observed in June, approximately 60 mm. Let's note seasonal trends. For spring, an increase in precipitation is noticeable, with a peak in May. For the summer, there is again a high amount of precipitation with a peak in June. For autumn, there is a gradual decrease in precipitation after September. Winter is characterized by relatively low rainfall, about 30 mm in December, less in January and February. The least rainfall is in March and February, which is approximately 20 mm. The rest of the months have rainfall in the range of 30 to 35 mm, which is the average for the region.

Consequently, the summer months have the highest levels of precipitation, which is typical for most regions of Ukraine, where summer thunderstorms can bring significant amounts of rain. The winter months have the least rainfall, which is also expected due to low temperatures and less moisture in the atmosphere.

In general, the Mykolaiv region has a pronounced continental climate with wetter summer months and dry winters.

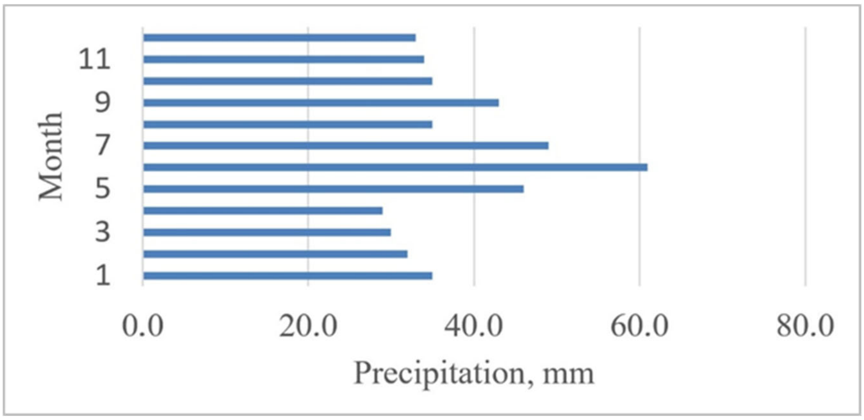

Fig. 2. Average monthly precipitation (mm) in Mykolaiv region during 1981-2024

The data in Table 2 indicate that, according to the moisture coefficient of Selyaninov, the Mykolaiv region belongs to the regions with an almost dry climate. In general, such conditions are observed for a larger area of the region. The Selyaninov moisture coefficient (GTC) with a value of 0.71 indicates insufficient moisture. This means that the amount of rainfall is insufficient for the normal development of plants, and they can suffer from a lack of moisture. The consequences of such insufficient moisture are: deterioration of conditions for the growth and development of crops; reduced yield due to lack of moisture; and the need for additional irrigation to maintain the normal development of plants. For natural ecosystems, this is: stress, which can lead to a decrease in biodiversity; impact on forests and natural meadows; lowering the groundwater level; reduction of river flow, and filling of water bodies.

In general, the Mykolaiv region is characterized by high atmospheric temperatures, precipitation deficit, and increased wind speed. Moisture deficiency can begin in April and end in October. During this period, as a rule, about 170 days with high temperatures are observed, which will affect the state of aquatic ecosystems, causing eutrophication phenomena.

It was determined that during the first half of the warm period from April to June, 25-35% of the total number of cases of spontaneous precipitation is observed in the northern Black Sea region, with a separation of 100 km from the coast, and the number of such cases increases by almost 50%. Snowfalls in the region can form from October to April. Features of snowfalls during this period: from October to November they can be unstable and melt quickly, there is a possibility of frost; from December to February, the most intense and stable snowfalls, which form a stable snow cover; From March and April lead to a long winter, melting snow can lead to flooding and rising water levels in rivers and lakes. A long period of snowfall has a number of positive aspects of the impact on water resources due to the provision of water accumulation in the form of snow cover, which gradually melts and replenishes water resources in spring.

Table 2. The value of precipitation and the Selyaninov GTC during 1981-2024

Indicator	Season	Mykolaiv region	Mykolaiv
Precipitation, mm	Winter	90	104
	Spring	100	105
	Summer	125	150
	Autumn	97	114
	Year	409	469
GTC	Warm season	0.71	0.83

In general, in winter, the region has 20.3 days with snow and 13.5 days with heavy snow. 80% of days with snow and 72% with heavy snow are observed in winter. The greatest recurrence of snow precipitation is observed in January (data from Table 1). It is believed that snowfall, in which more than 20 mm falls in 12 hours, is a natural meteorological phenomenon. A phenomenon of this intensity is observed once every four years. Precipitation in the form of snow prevails in January. Precipitation in the form of wet snow per year in the Mykolaiv region is observed for about 4 days. At the same time, in the Mykolaiv region over the past decades, there has been a change in the humidification regime. There is a steady trend of decreasing the amount of precipitation per year from 1961 to 2024. Graph Fig. 3 shows that the amount of precipitation in 10 years decreases by an average of 1.7%.

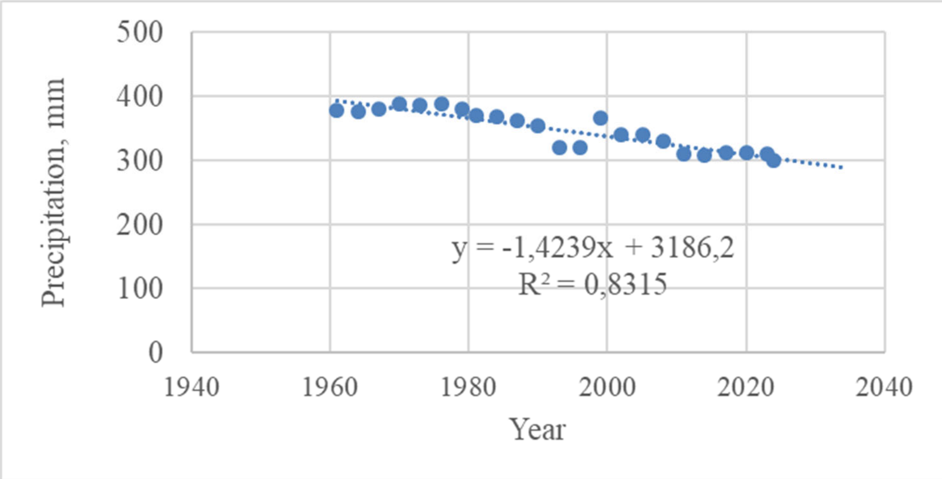

Fig. 3. Annual change in the amount of precipitation during 1961-2024 in the Mykolaiv region

Graph Fig. 3 indicates a coefficient of determination $R^2 = 0.83$, which means 83% of the variation in data values can be explained by a linear trend line and a sustained downward trend. In other words, the linear model explains 83% of the variance of the dependent variable (values) based on the independent variable (years). This is a reasonably high value, which indicates that the trend line fits well with the data, although not perfectly. There are still 17% of variations that are not explained by this model. These can be random variations or the influence of other factors that were not considered in the model. The linear model allows you to make a forecast for the future, assuming that the trend continues. However, actual data may vary due to various factors.

We also consider it necessary to note an interesting pattern that the average annual rainfall during 1991-2024 has not undergone significant changes compared to 1961-1990 (Fig. 4). In general, the shapes of both curves are similar, indicating similarities in the seasonal distribution of precipitation in both periods. The main peaks and troughs in precipitation remain in the same months, with some variations in absolute values. However, it should be noted that there is a redistribution of precipitation between seasons of the year. So, the most significant changes occur for the autumn period. Within the region, the amount of precipitation increased by about 16% due to October (47%) and September (18%). However, in November, the amount of precipitation decreased slightly by 6%. At the same time, there is a slight increase in the amount of precipitation in spring due to May by 7% and in summer due to June by 6%, which is not significant for a radical change in climatic conditions. For other months of the year, there is a significant decrease in precipitation due to April by 17%, July by 18% and August by 20%. Such a significant decrease in precipitation during almost 60 days of the year leads to a significant increase in the maximum temperature of atmospheric air, an increase in aridity (Fig. 4). The data indicate certain climatic changes in the region, in particular, the redistribution of precipitation throughout the year. So, the most significant changes occur for the autumn period. The total seasonal precipitation for Autumn increased by about 16%. This seasonal increase was primarily driven by significant positive anomalies in precipitation amounts during two months: October (increased by 47%) and September (increased by 18%) compared to the 1961-1990 period. However, in November, the amount of precipitation decreased slightly by 6%.

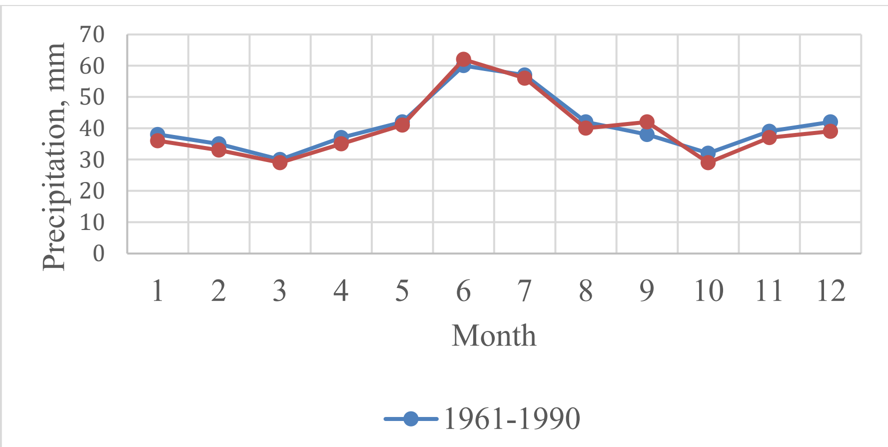

Fig. 4. Dynamics of the monthly precipitation rate in the region during 1991-2024 compared to the period of 1961-1990

It should be noted that against the background of a decrease in the total number of days with precipitation, the number of heavy rains and snow increased. Thus, an increase in the temperature of atmospheric air in winter led to an increase in the number of days with wet and heavy sleet. At the same time, we consider it necessary to emphasize that an increase in the amount of precipitation in the form of heavy sleet, snow, and rain, as well as an increase in the maximum temperature of atmospheric air, does not provide sufficient accumulation of moisture in the soil cover and nutrition of aquatic ecosystems.

Annually up to 7 days are observed in the region, which are characterized by atmospheric drought, the environmental consequences of which are: land degradation due to desertification and loss of soil fertility; depletion of water bodies (water level in rivers, lakes and underground aquifers can be significantly reduced); pollution of aquatic ecosystems (reducing water in water bodies can increase the concentration of pollutants); loss of habitats (plants and animals can lose their habitats due to the drying up of water sources and land degradation); population decline (some species may decrease in numbers or even disappear).

4. Conclusions and Prospects

The study confirmed that rainfall regime shifts are a direct and reliable indicator of the increasing hydrological vulnerability of Mykolaiv Oblast, which lies within the Northern Black Sea region.

The region is characterized by a persistent atmospheric precipitation deficit, with average annual figures critically ranging between 409 and 469 mm. The calculation of the Selyaninov hydrothermal moisture coefficient (HTC) (0.71) consistently demonstrates the predominance of very dry and moderately dry conditions over many years, unequivocally confirming a clear tendency towards aridization (desertification) in the southern districts.

The main climate factors driving hydrological vulnerability are not merely the total quantity, but the significant shifts in the pattern of fallout. A seasonal imbalance and an increase in intense, short-duration storm events have been recorded. This paradoxically diminishes the effectiveness of soil moisture penetration and generates rapid surface runoff, increasing the risks of both soil drought and flash flooding.

These shifts negatively impact the stability of aquatic ecosystems, notably leading to the shallowness of the Southern Buh River, land degradation due to desertification, depletion of water bodies, and a decrease in biodiversity.

The findings necessitate the urgent development of integrated adaptation strategies to enhance water resilience in the region. Further research should focus on modeling the impact of projected rainfall changes on agricultural production and on developing measures for efficient water resource management.

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