ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2022, Vol. 58, No. 12, pp. 1458–1469. © Pleiades Publishing, Ltd., 2022.
Russian Text © The Author(s), 2022, published in Issledovanie Zemli iz Kosmosa, 2022, No. 4, pp. 25–37.

USE OF SPACE INFORMATION ABOUT THE EARTH
STUDYING SEAS AND OCEANS FROM SPACE

Cold Spot over the Lofoten Vortex

V. S. Travkin[a, *], T. V. Belonenko[a], and A. A. Kubryakov[b]
[a] *Saint Petersburg State University, Saint Petersburg, Russia*
[b] *Marine Hydrophysical Institute of the Russian Academy of Sciences, Sevastopol, Russia*
**e-mail: v.travkin@spbu.ru*
Received December 10, 2021

Abstract—The paper provides a joint analysis of Aqua/MODIS data, global ocean reanalysis GLORYS12V1, and atmospheric reanalysis ERA5. We consider the quasi-permanent Lofoten Vortex located in the Norwegian Sea. Analysis of SST maps reveals the existence of a cold spot in the area of the Lofoten Vortex in the summer–autumn period. A joint analysis of satellite maps and GLORYS12V1 data shows that the main reason for the formation of the cold spot is the rise of the isopicns of the upper dome of the vortex and the destruction of the heated layer, as a result of which colder isopicns come to the surface. It is revealed that in many cases the cold spot shifts to the periphery of the vortex in a southeasterly direction, and the shift can be several tens of kilometers. The reason may be the vortex advection of particles in an anticyclonic vortex. It is shown that along with the formation of the cold spot, there is a 10–30 m decrease in the depth of the upper quasi-homogeneous layer above the Lofoten Vortex in the summer–autumn period. The formation of a cold spot on the water surface is accompanied by a decrease in temperature in the drive layers of the atmosphere.

Keywords: Lofoten Vortex, lens, cold spot, heated layer, Aqua/MODIS, GLORYS12V1, reanalysis ERA5, SST, SSH

DOI: 10.1134/S0001433822120246

INTRODUCTION

The interface between the ocean and the atmosphere is a complex thermodynamic system in which processes of various physical nature continuously occur, transferring energy from one area of the system to another. The World Ocean is the largest underlying surface of the atmosphere, playing a key role in its variability by absorbing and releasing most of the solar energy into the atmosphere (Sun and Wu, 2021). The redistribution of heat in the World Ocean from the tropics to the polar regions is significantly affected by the meridional thermohaline circulation (Richards and Straneo, 2015). The development of deep convection in winter at high latitudes leads to the vertical sinking of warm and saline waters and the subsequent formation of deep currents, which are the lower branch of the meridional thermohaline circulation. At the same time, a significant effect of mesoscale eddies on changes in the thermohaline characteristics of local water masses is observed (Richards and Straneo, 2015; Belonenko et al., 2020). When the water surface interacts with the atmosphere, part of the heat is released and passes into the atmosphere. Particularly active regions of the ocean, where the exchange of energy with the atmosphere occurs most intensively, are called "ocean–atmosphere interaction centers" (Timonov et al., 1970; Lappo et al., 1990). In the North Atlantic, in the current conditions of global warming and the formation of short-term climate fluctuations, the centers of interaction between the ocean and the atmosphere are of great importance. One of them is the Norwegian energy-active zone, with its center in the Lofoten Basin, located in the deep part of the Norwegian Sea. The proximity to the Arctic Basin and the role of the Lofoten Basin as a transit region for Atlantic waters leads us to consider its climatic significance to be extremely important (Malinin and Shmakova, 2018). In the central part of the basin, where an increase in the thickness of Atlantic waters in the intermediate layer is observed and where the quasi-permanent anticyclonic Lofoten Vortex is located, there is an active heat transfer from the ocean to the atmosphere (Richards and Straneo, 2015; Novoselova and Belonenko, 2020; Fedorov et al., 2021). This contributes to the active development of deep winter convection and the renewal of deep Atlantic waters.

The estimate of the average annual values of the total heat transfer (the values of the turbulent heat flux and heat losses due to evaporation) in the Norwegian energy-active zone with the center in the Lofoten Basin is 125 W/m^2 (Malinin and Shmakova, 2018). In winter, the Lofoten Basin is characterized by heat losses on the order of 80 W/m^2 (Isachsen et al., 2007; Richards and Straneo, 2015), which contributes to the development of convection down to depths of more than 1000 m (Yu et al., 2017; Raj et al., 2015; Fedorov et al., 2019).

Heat loss in the ocean is associated with its cooling. Changes in the stability and roughness of the sea surface, as well as fluctuations in wind speed, contribute to the development of surface heat-flux anomalies. An increase in sea surface temperature (SST) leads to an increase in heat flow, while a decrease in it contributes to less upward heat flow, while lower wind speeds lead to a significant adaptation of atmospheric humidity and temperature to the rapidly changing SST, which in turn contributes to smaller heat-flow anomalies (Hausmann et al., 2017).

The passage of the wind over relatively strong SST gradients associated with vortices and ocean fronts promotes the development of vertical and horizontal movements in the underlying layers due to the weakening of stratification. This leads to a further increase in the difference between SST and air temperature near the sea surface, especially at high background wind speeds (Small et al., 2019). The net heat flux at the ocean–atmosphere interface is equal to the sum of the solar heat fluxes (long-wave and short-wave radiation) and turbulent fluxes (latent and apparent heat fluxes). The SST values have a direct impact on the estimates of long-wave radiation and apparent heat fluxes into the atmosphere (Kumar et al., 2011).

The work (Sun and Wu, 2021) investigates the spatial relationship between turbulent heat flow at the surface and water temperature at the surface. Numerical modeling results show a correlation between SST and assessments of apparent heat flux, indicating a close relationship between the ocean and the atmosphere. On the other hand, the negative correlation between these characteristics indicates that heat loss from the ocean surface contributes to a decrease in SST, which is indicative of the influence of the atmosphere on the ocean. Other studies point to differences between the ocean–atmosphere flows associated with mesoscale vortices and much larger forms. At scales less than 1000 km, the wind speed is proportional to the SST anomalies, and the divergence and vorticity of the wind stress is proportional to the zonal and meridional SST gradients (Schneider et al., 2015). The Lofoten Basin is a thermal reservoir of Atlantic waters, the deepening of which in the basin determines not only the structure of its water masses, but also the features of the ocean–atmosphere interaction processes (Novoselova and Belonenko, 2020; Fedorov et al., 2021). Surface heat transfer in the Lofoten Basin is dominated by the contribution of the mean flow from the south and eddy advection from the east.

BRIEF INFORMATION ABOUT THE LOFOTEN VORTEX

The Lofoten Vortex (LV) is located in the deep part of the basin (Fig. 1). The most probable position of the center of the vortex according to the contact data is 70°N, 3.5°W (Søiland et al., 2016), and according to modeling data, LV localization occurs in the region of 69°–70°N, 3°–5° E. The LV is characterized by a local maximum of sea level and vortical kinetic energy (Volkov et al., 2015; Travkin and Belonenko, 2021). Winter convection is a necessary condition for the existence of this unique natural phenomenon, as it creates favorable conditions for its annual regeneration (Bloshkina and Ivanov, 2016; Bashmachnikov et al., 2017). Another mechanism that contributes to the maintenance of high anticyclonic vorticity in the center of the basin is the capture of mesoscale vortices detached from the Norwegian Current (Belonenko et al., 2014; Volkov et al., 2015). The thermohaline characteristics of the LV with a warm and saline core differ significantly from the characteristics of the surrounding waters (Yu et al., 2017; Belonenko et al., 2018; Travkin and Belonenko, 2019).

In this paper, satellite maps of SST (Sea Surface Temperature) and SSH (Sea Surface Height) are analyzed together. Analysis has revealed that the SST values are lower in the area of the LV. This means that a cold spot is formed on the surface of the water, as well as in the near-water layer of the ocean above the warm LV. An analysis of the possible causes of the observed phenomenon is the aim of this work.

DATA AND METHODS

All analyzed data are obtained from open sources. Their description is presented in Table 1.

We used GLORYS12V1 data on the Mixed Layer Depth (MLD) calculated by the Kara method (Kara et al., 2000), which allows us to define the depth of the mixed layer as the value of the depth at which the temperature of the water has changed by a certain amount compared to the surface:

$$\Delta\sigma = \sigma(T_r, S_r) - \sigma(T_h, S_h),$$

where $\Delta\sigma$ is an empirical criterion for the density of sea water, equal to the difference between the density on the sea surface $\sigma(T_r, S_r)$ and $\sigma(T_h, S_h)$, the density of water with the same salinity, but at a temperature that is 0.2°C less than on the sea surface. The first horizon where the density difference exceeds $\Delta\sigma$ is considered the depth of the MLD. This method can only be used for high-resolution vertical profiles.

RESULTS

Observations of a Cold Spot over the Lofoten Vortex and Its Seasonal Course according to the GLORYS DATA

The map of average SST satellite data Aqua/MODIS in the study area, constructed with averaging for 2002–2019, reveals a cold spot above the LV with a temperature of 1–2°C below the surrounding waters (Fig. 2). The frequency of occurrence of the given cold spot has a seasonal variation. The maps based on average monthly data show that the cold spot

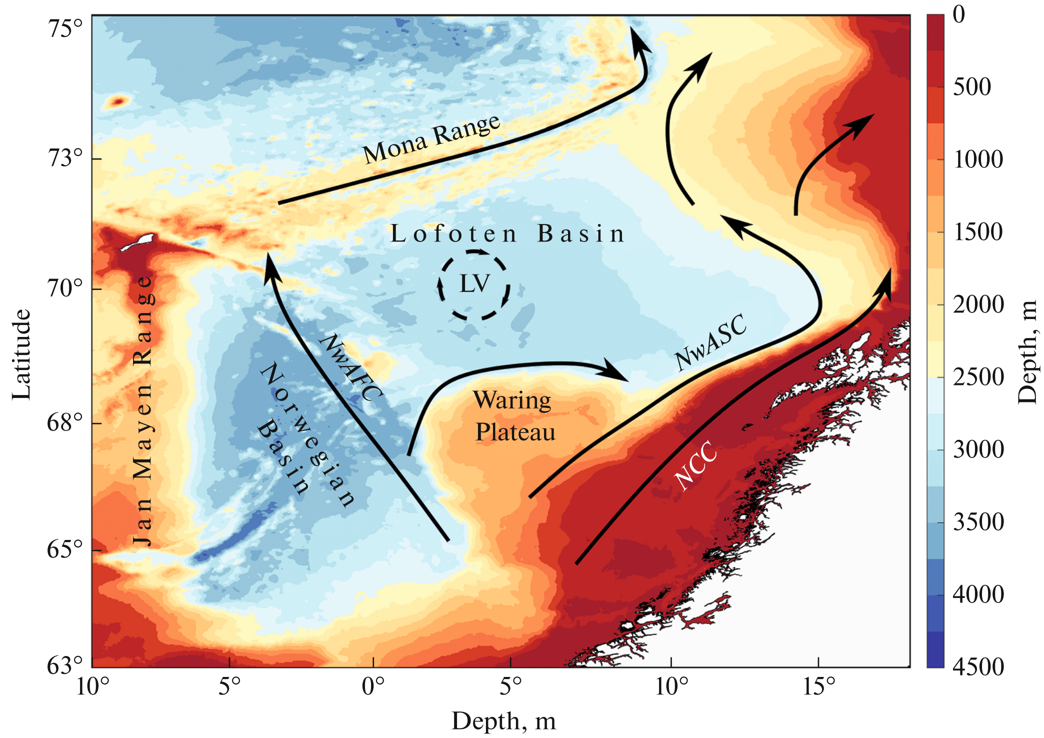

Fig. 1. Study area. The position of the anticyclonic Lofoten Vortex is shown as a circle. The area of the most probable location of the LV is shown by the dotted line. The bottom topography (m) is shown in color, and the branches of the Norwegian Current are shown in black arrows (international designations are used (Volkov et al., 2015)): *NwASC*—Norwegian Slope Current; *NCC*—Norwegian Coastal Current; *NwAFC*—Norwegian Frontal Current.

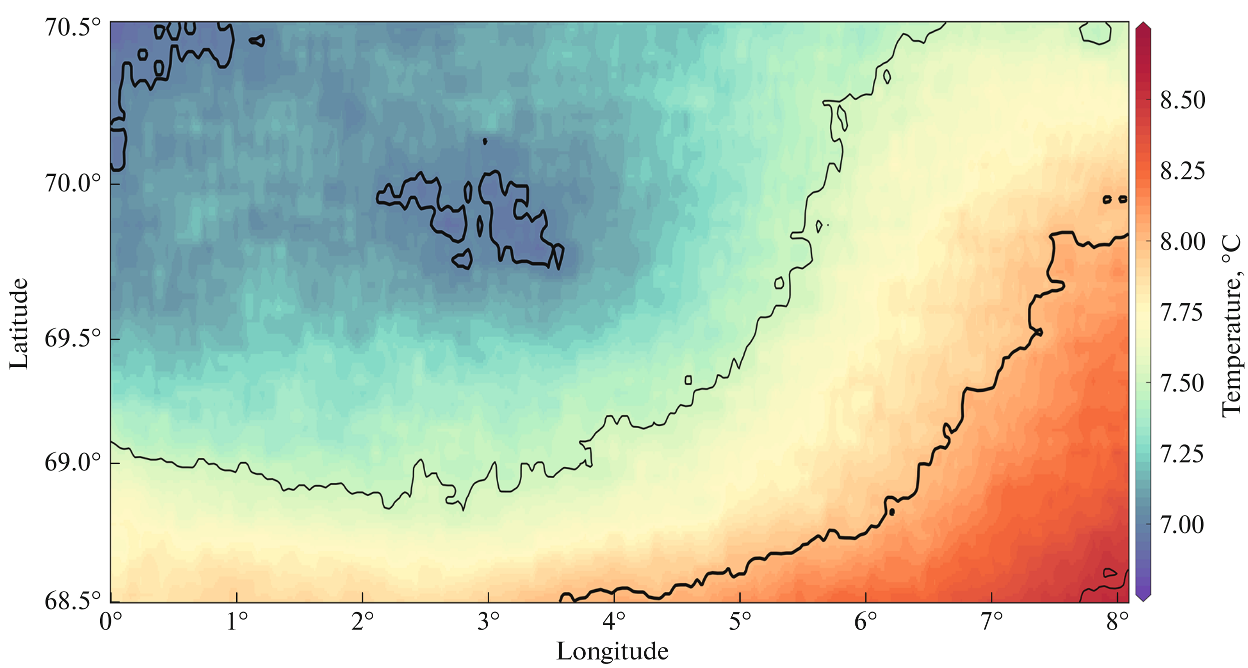

Fig. 2. Average SSTs according to Aqua/MODIS data for the period 1999–2019.

Table 1. Data used

Product	Description	Source
Aqua/MODIS (Level 3 Standard Mapped Image (SMI)	Average monthly SST measurements for the period 2002–2019. Spatial resolution—4.63 km. The data were obtained using channels 31 and 32 (daytime observations, IR range, a wavelength of 11 and 12 μm, respectively) of the scanning spectroradiometer of medium resolution (Moderate-resolution Imaging Spectroradiometer, MODIS). MODIS provides global coverage of the Earth's surface every 1–2 days with high radiometric resolution (12 bits). The Level 3 array (SMI) is data for a certain period of time, projected onto a spatial grid, while at each point there is an average value of the desired parameter for the specified period	http://oceandata.sci. gsfc.nasa.gov
GLORYS12V1	Monthly average temperature data, zonal and meridional velocity components *u* and *v*, MLD estimates of the GLORYS12V1 reanalysis for the period 1999–2019. The data is available on the CMEMS (Copernicus Marine Environment Monitoring Service) portal. The GLORYS12V1 product is a vortex-resolving reanalysis of the World Ocean with a spatial resolution of 1/12° at 50 horizons. The reanalysis is based on the NEMO model with ECMWF ERA-Interim forcing. The GLORYS12V1 data assimilate together satellite altimetry data, sea surface temperature (Reynolds 0.25°C AVHRR), sea ice concentration, and *in situ* vertical profiles of temperature and salinity. Observations are assimilated using the Kalman filter. The time discreteness of the data is one day	https://resources.marine.copernicus.eu
ERA5	ERA5 is a fifth-generation reanalysis of ECMWF for global weather and climate analysis over the past 40–70 years. ERA5 replaces the previously used ERA-Interim reanalysis. The reanalysis combines model data and observational data through their assimilation. It is based on the method used by numerical weather-prediction centers where every few hours (12 hours in ECMWF), the previous forecast is optimally combined with newly available observations to produce a new best estimate of the state of the atmosphere, from which an updated, improved forecast is produced. ERA5 provides hourly estimates of a large number of atmospheric, oceanic, and terrestrial parameters. The spatial resolution of the reanalysis data is 0.25° × 0.25°	https://cds.climate. copernicus.eu

exists only in the summer–autumn period, while it is absent in winter and spring. The formation of the cold spot above the LV begins in June. During this period, a seasonal thermocline gradually forms, the vortex begins to acquire a lenticular shape and a vast area of low SST values appears on the water surface. By July, this area is localized in the area of the location of the LV and the cold spot appears most clearly in August–October.

In November, a decrease in temperature over the LV is also noted on the average monthly maps (Fig. 3).

A decrease of several degrees in the water surface temperature in the area of the Lofoten Vortex is confirmed by multiple satellite SST images in different seasons; however, in most cases, a "cold spot" above the eddy is observed in the warm season, most often in August–September. We analyzed the SST maps for individual months (MODIS for 2002–2019 and GLORYS12V1 for 1999–2019) and found that the average temperature anomaly above the eddy is 1–2°C, but in some years it is as high as 4°C.

Vertical Structure of LV and Its Features in Different Seasons according to GLORYS Data

To analyze the causes of the appearance of the cold spot and the seasonal variation of SST in the vortex, the vertical structure of the vortex was studied based on the reanalysis GLORYS12V1. These data demonstrate that the LV has a pronounced lenticular structure, in agreement with previous works (see, e.g., Volkov et al., 2015; Bloshkina and Ivanov, 2016;

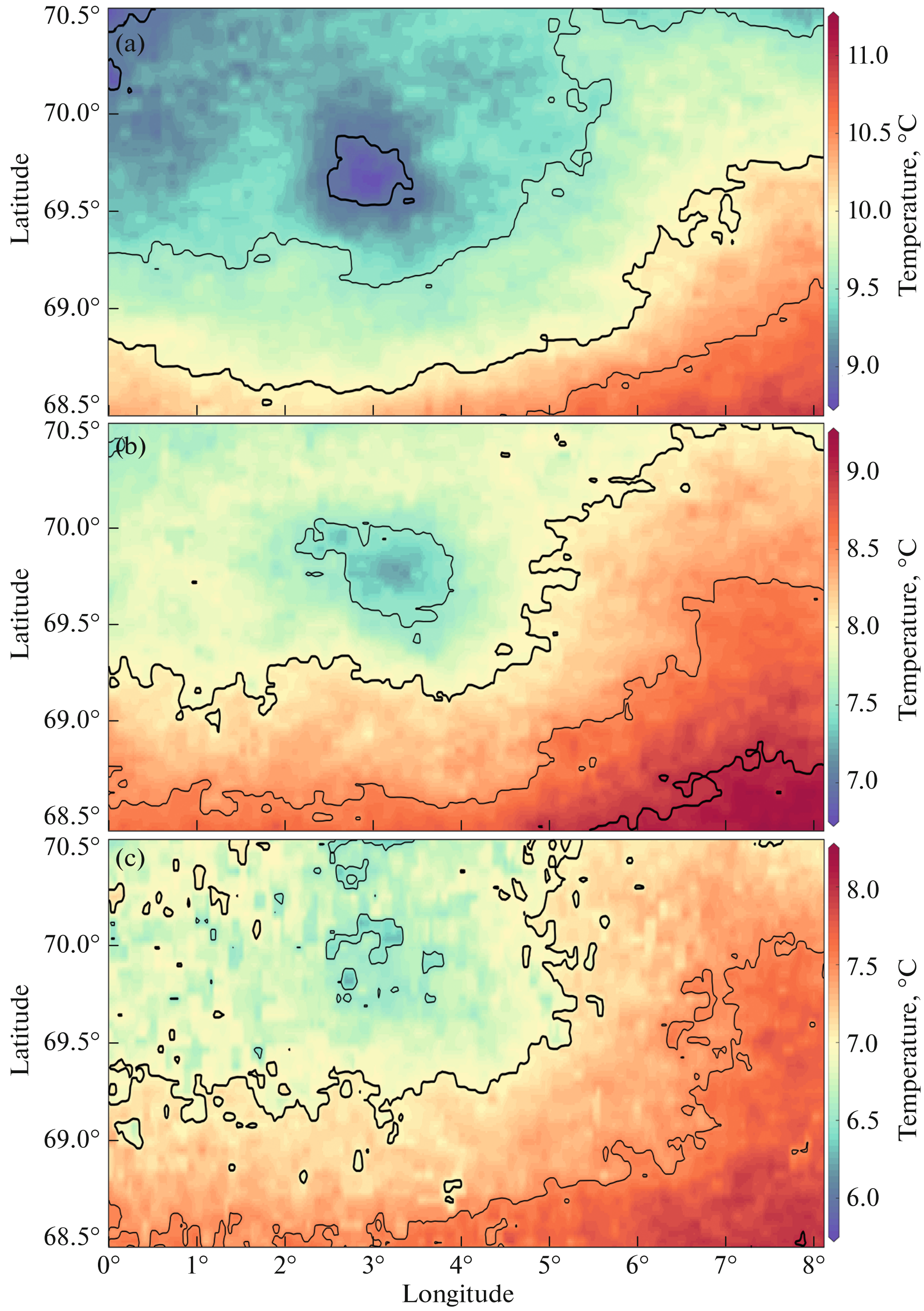

Fig. 3. Average monthly SST maps (September–November) for the period 1999–2019.

Belonenko et al., 2018; Travkin and Belonenko, 2019). The lens core is located at depths of 200–800 m (Fig. 4a). At the top of the dome, positive vertical velocities cause deep water to rise. This process pushes cold waters to the surface and causes the observed cold anomaly to appear on the surface. In all cases, a cold spot in the region of the LV is formed during periods when the lens is already formed and well-developed. In August and September, the lens reaches its maximum values (Novoselova, 2022), and these months show the largest SST gradients in the area of the LV (Fig. 4b).

Displacement of the Cold Spot Relative to the Center of the Vortex

A joint analysis of the SST and SSH maps reveals the following feature: in many cases, the cold spot on the vortex surface shifts to its periphery relative to the center. For example, Fig. 5 shows that the center of the SSH anomalies has the coordinates 70.08° N, 3.08° E, while the center of the SST anomalies is 69.73° N, 4.06° E; i.e., the cold spot is located to the southeast of the LV center and the distance between the centers

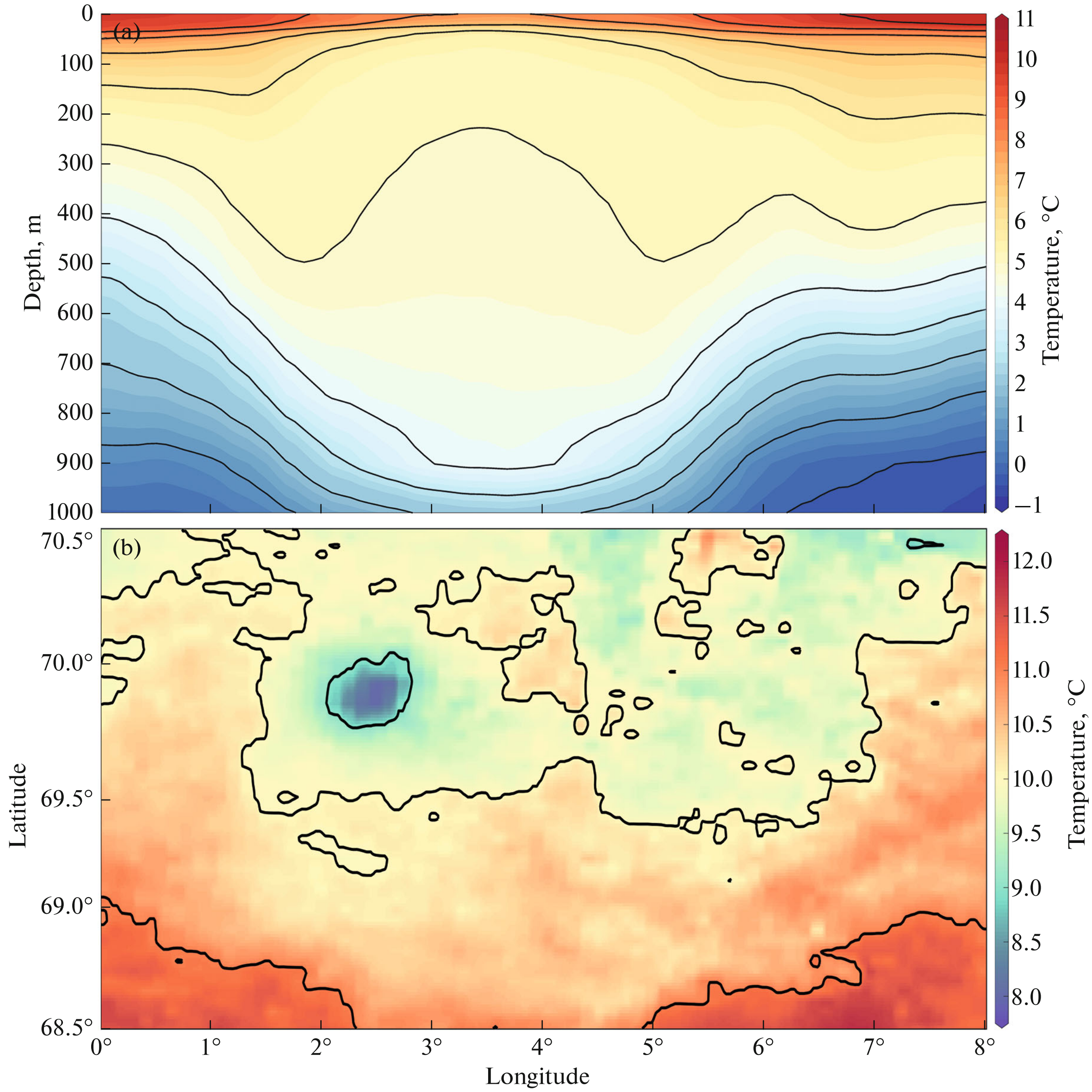

Fig. 4. Vertical section through the core of the Lofoten Vortex at 69.8°N. Temperature fields according to GLORYS12V1 reanalysis data for August 2010 (a) and SST map according to MODIS data (b).

is 46 km. In the Lofoten Basin, colder waters are located in the northern and northwestern parts of the vortex (Sandalyuk et al., 2020), and this is consistent with the scheme of the main currents in the region (Richards and Straneo, 2015). The LV scale on the surface can reach 100 km (Fig. 5a), and the cold spot moves from the north to its southeastern periphery (Fig. 5b).

We analyzed jointly the SSH and SST images constructed from monthly average data for each month of 1999–2019 and found that the shift of the cold spot to the southeast is typical mainly of August and September, i.e., when the lens reaches its maximum size (Novoselova, 2022). In total, we considered 199 pairs of joint distributions of SSH and SST, of which in 102 cases (51%) the distance between the centers did not exceed 10 km (Fig. 6). In other cases, the negative SST anomalies corresponding to the cold spot above the vortex shifted to a greater extent relative to the SSH anomalies to the southeast. In 19% of cases, the cold spot shifted over a distance in the range of 10–20 km, in 7%, over distances in the range of 20–30 and 40–50 km, and in 4%, over distances of 30–40 km. It should be noted that the distances between the centers were determined automatically, and when the distances between the centers of the anomalies exceeded

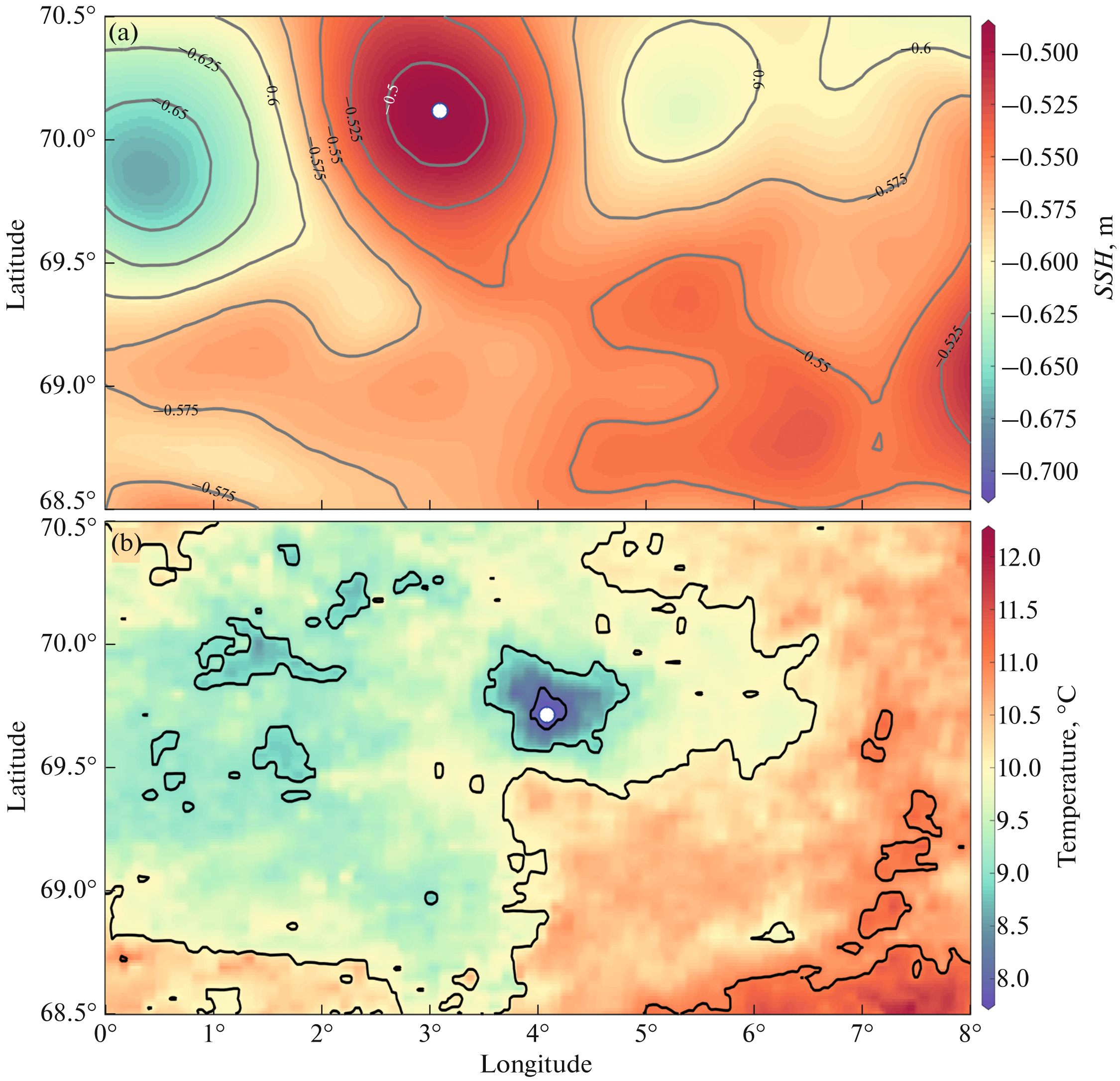

Fig. 5. SSH maps according to GLORYS12V1 (a) and SST according to Aqua/MODIS data (b) for August 2004. The dots show the geometric centers of the anomalies.

the vortex radius of 50 km, it is possible that the method would take into account the centers of anomalies related to different vortex structures, so we will not consider them further.

Near-Surface Air Temperature over the Lofoten Vortex

Figure 7 shows that the cold spot above the LV, formed as a result of a decrease in surface water temperature, leads to a decrease in air temperature in this area. ERA5 atmospheric reanalysis data confirm the presence of negative anomalies in the surface air temperature at a height of 2 m during the existence of the cold spot above the vortex. All this means that during the formation of the cold spot, heat fluxes into the atmosphere decrease.

Mixed Layer Depth above the Lofoten Vortex

The appearance of the cold spot in the summer–autumn period above the LV is accompanied by a decrease in the depth of the upper quasi-homogeneous layer (MLD) in the vortex. Figure 8*b* shows that the minimum MLD values in September 2003 are observed directly above the LV lens. The cold spot is localized at 69.8° N, 1° E (Fig. 8a). It can be seen that the minimum values of the MLD are also achieved here (Fig. 8b). While in the vortex the UQL values are only 20 m, outside the vortex they exceed 30 m (Fig. 8b). This is what contributes to the reduction of the MLD over the vortex.

A joint analysis of the satellite maps and vertical sections based on the GLORYS12V1 data shows that the minimum MLD values above the lens are characteristic of the summer–autumn months and persist

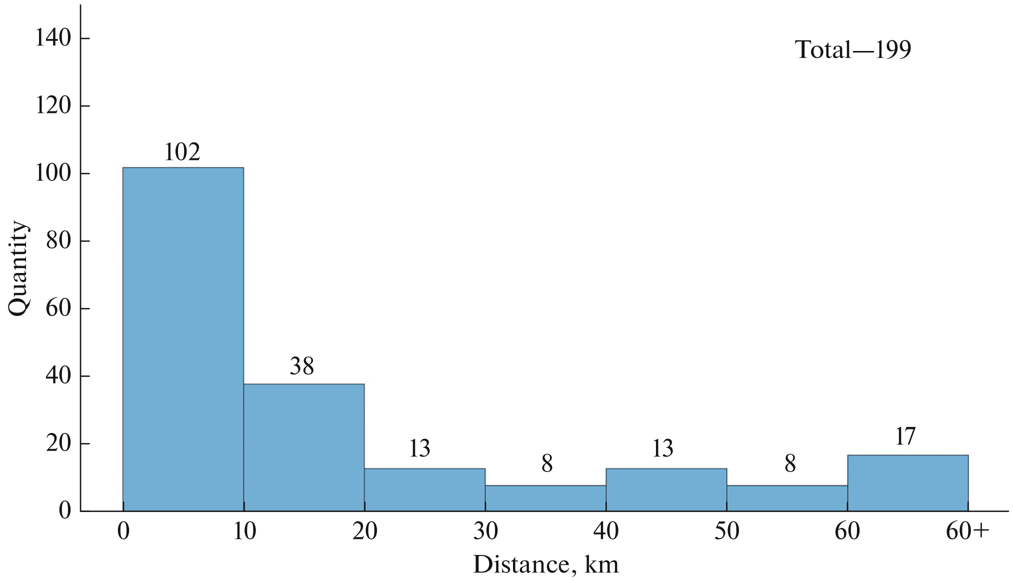

Fig. 6. Number of shift observations between SSH and SST anomaly centers on satellite maps.

until the onset of winter convection. In autumn, the MLD values above the lens gradually begin to increase. In November, the lens still retains its shape (Fig. 9a), but the MLD estimates in the region of the vortex location are as high as ~70 m. It can be seen that individual isopycnals above the lens come to the surface in November 2000, which subsequently leads to the destruction of the lens and the onset of winter convection (Fedorov et al. 2018; Travkin and Belonenko, 2020). Outside the vortex area, the MLD estimates are much larger and exceed 90 m (Fig. 9b), although even in September the MLD depth above the lens does not exceed 10–20 m, and outside the vortex region, these estimates are 30–40 m greater (not shown).

DISCUSSION AND CONCLUSIONS

The warm and salty Atlantic water in the Lofoten Basin occupies a vast area, forming a huge thermal reservoir in the Norwegian Sea (Belonenko et al., 2020). When the water surface interacts with the atmosphere, part of the heat is released and passes into the atmosphere. The LV is the center of the Norwegian energy-active zone, where the maximum heat transfer to the atmosphere occurs. An increase in heat transfer occurs mainly in winter and is characterized by a negative buoyancy flux in the upper layers of the ocean (Isachsen et al., 2007; Richards and Straneo, 2015; Malinin and Shmakova, 2018). In the summer–autumn period, heat-transfer processes weaken, and in the area of the LV location, according to satellite images, a cold spot is observed with a temperature that is lower than the water temperature outside the vortex. At the same time, the reference temperature of the air

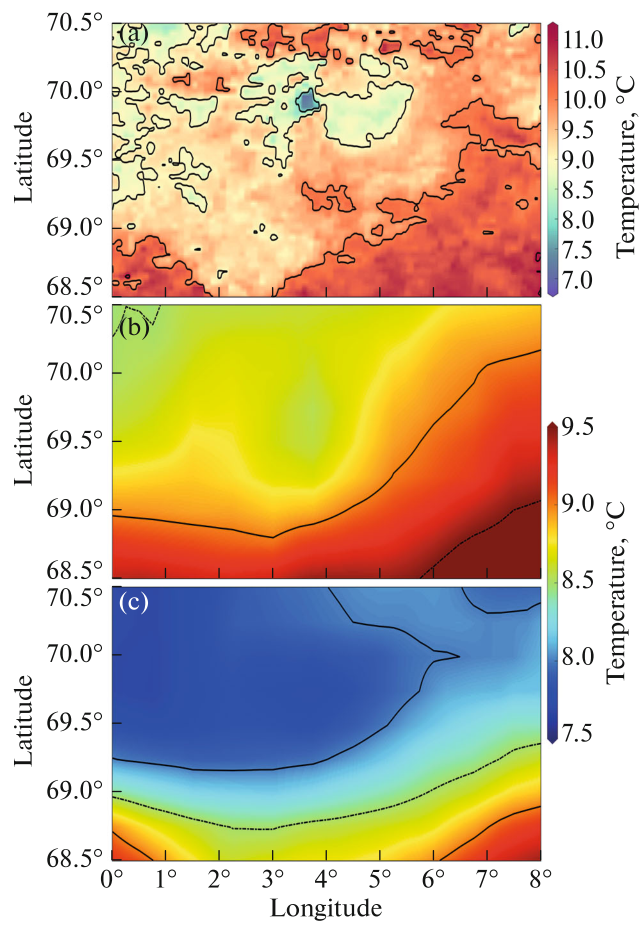

Fig. 7. SST map based on September 2004 averaged MODIS data (a); air temperature in the Lofoten Basin at an altitude of 2 m above sea level according to ERA5 for 22 (b) and September 29, 2004 (c).

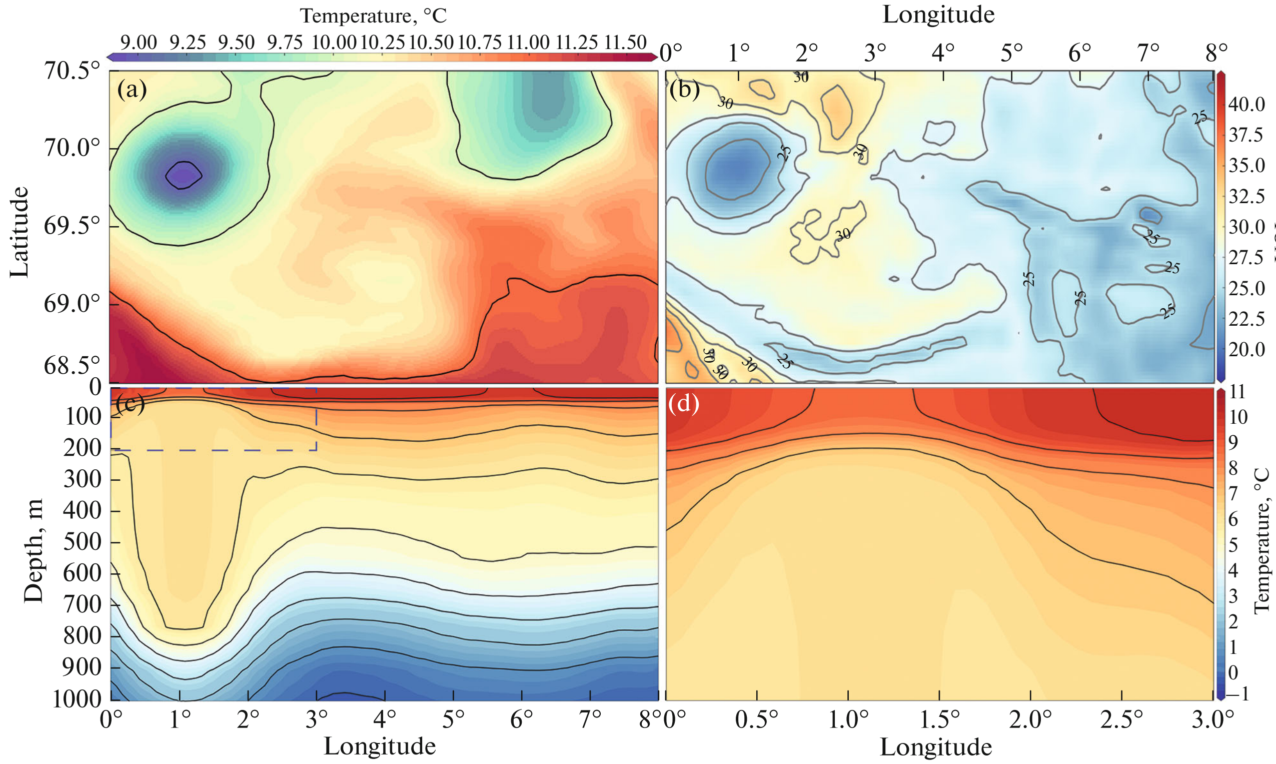

Fig. 8. Ocean surface temperature distribution according to GLORYS12V1 (a), UQL estimate (b), and a vertical temperature section along the latitude 69.8° N. in the LV (c, d) in September 2003.

in contact with the water surface also has lower values in the summer period.

The work (Bloshkina and Ivanov, 2016) reproduces in detail the annual life cycle of the LV, the shape of which changes throughout the year. In the winter–spring period, convective processes dominate, when the seasonal thermocline collapses, and winter convection determines the evolution of the vortex, reaching 1000 m at the center of the vortex (Fedorov et al., 2019). During this period, the vortex acquires the shape of a semi-ellipsoid (Mikaelyan et al., 2020). In the summer–autumn period, the LV is represented in the form lenses with warm and salt water.

The formation of a lens is accompanied by the destruction of the upper heated layer with elevated temperatures and the emergence of underlying isotherms with lower values relative to the surrounding water. We analyzed the monthly average distributions of MODIS over the period 2002–2019 and plotted the corresponding vertical sections through the center of the LV using the GLORYS12V1 data with monthly averages. A joint analysis of satellite maps and GLORYS12V1 data shows that the outer dome of the lens compresses the isopycns, lifting them up and destroying the surface heated water layer. Colder water from the lower horizons rushes upward, and a "spot" with lower temperatures forms on the surface. As a result, in the vortex area, isopycnal surfaces corresponding to the lower layers with lower temperatures come to the surface (see Figs. 4a, 8b, and 9a). Thus, the main reason for the appearance of the cold spot above the lens is the rise of isopycnes directly above the lens in the summer–autumn period.

The seasonal modulation of the manifestation of a cold spot is associated primarily with the conditions of vertical mixing: in summer, sharp heating masks the rise of the isopycnes above the lens, and in winter, deep convection destroys the upper part of the dome. The cold spot most clearly manifests itself in August and September, during the period of thermocline destruction and MLD deepening.

A joint analysis of the SSH and SST maps based on the Aqua/MODIS and GLORYS12V1 data reveals a southeastward shift of the SST cold spot relative to the SSH. This mismatch of centers is a consequence of vortex advection, in which the anticyclonic rotation of particles with low temperatures located in the north and northwest transfers these particles to the southeastern periphery of the Lofoten Vortex. It was shown by (Kubryakov et al., 2016) that the distribution of temperature anomalies in a vortex depends on the vortex polarity. Cold water entering the anticyclone from the north and northeast is mechanically transported to the southeast of the vor-

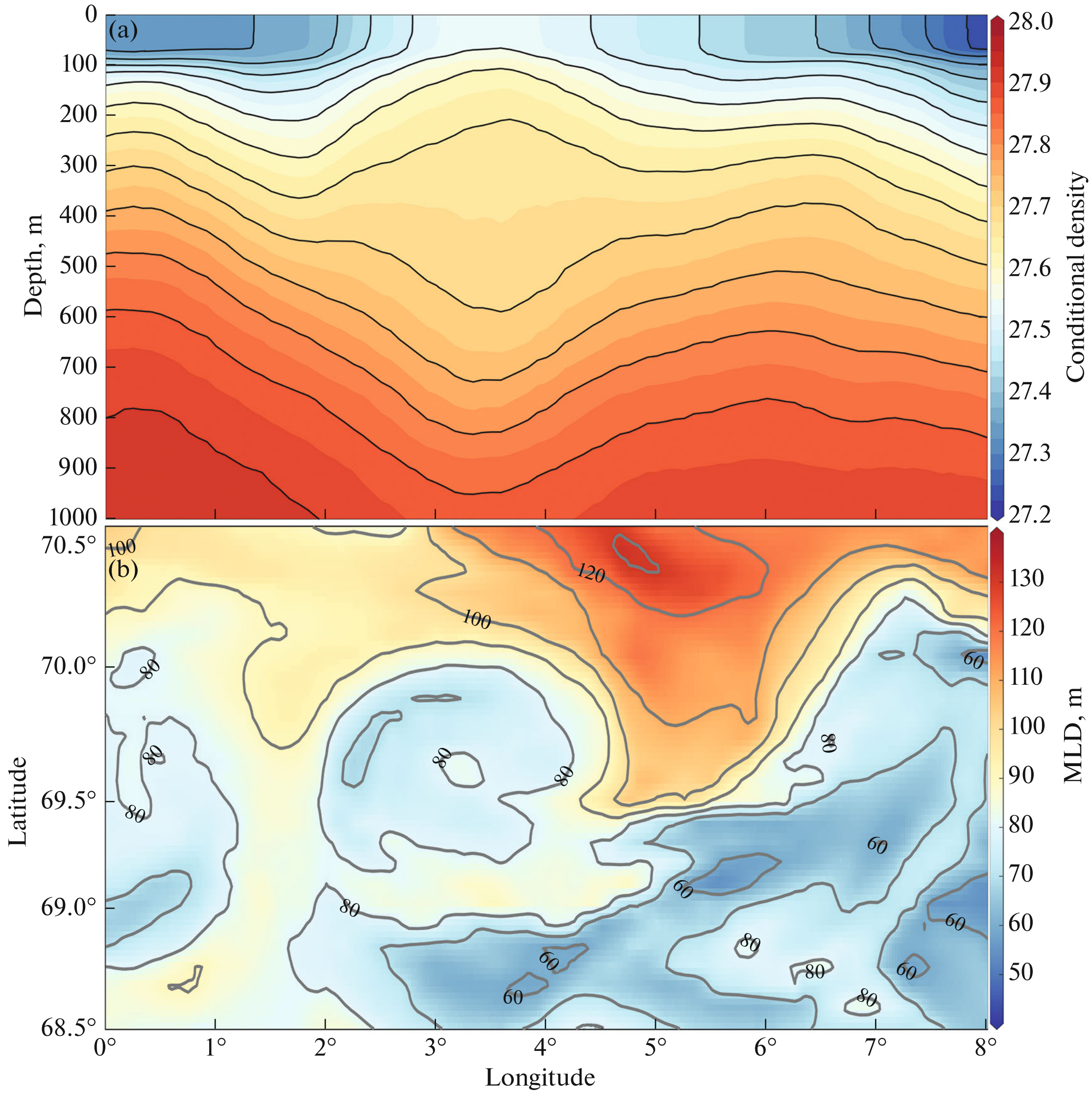

Fig. 9. Density distribution (a) and MLD estimate (m) (b) in LV in November 2000 according to GLORYS12V1 data.

tex during its evolution, thereby creating a shift of the SST anomalies relative to the SSH anomalies. This shift is most often observed in August and September (see Fig. 5).

The raising of the isopycnal in the vortex contributes to the decrease in the MLD depth in the vortex. This effect is most typically observed at the beginning of the summer season and reaches its maximum parameters in August and September, during the period of the greatest development of the intrathermocline lens; it continues through November. In this case, a decrease in the water surface temperature is accompanied by a decrease in the MLD in the area of the Lofoten Vortex. Indeed, the MLD decrease by 10–20 m directly above the lens is observed in August–September and reaches 30 m by November. Note that the observed MLD decrease above the vortex in the summer–autumn season has not been noted anywhere before. Perhaps this is due to the fact that MLD estimates are usually analyzed only for the winter months.

FUNDING

The seasonal evolution of the structure of the Lofoten Vortex was studied with the support of the Russian Science Foundation grant 21-77-10052.

REFERENCES

Bashmachnikov, I., Sokolovskiy, M., Belonenko, T., Volkov, D., Isachsen, P.E., and Xavier, C., On the vertical structure and stability of the Lofoten eddy in the Norwegian sea, *Deep-Sea Res., Part I*, 2017, vol. 128,

no. 5, pp. 1–27.
https://doi.org/10.1016/j.dsr.2017.08.001

Belonenko, T.V., Volkov, D.L., Norden, Yu.E., and Ozhigin, V.K., Water circulation in the Lofoten Basin of the Norwegian Sea, *Vestn. S.-Peterb. Univ., Nauki Zemle*, 2014, vol. 7, no. 2, pp. 108–121.

Belonenko, T.V., Koldunov, A.V., Sentyabov, E.V., and Karsakov, A.L., Thermohaline structure of the Lofoten vortex in the Norwegian Sea based on in-situ and model data, *Vestn. S.-Peterb. Univ., Nauki Zemle*, 2018, vol. 63, no. 4, pp. 502–519.

Belonenko, T., Zinchenko, V., Gordeeva, S., and Raj, R.P., Evaluation of heat and salt transports by mesoscale eddies in the Lofoten Basin, *Russ. J. Earth Sci.*, 2020, vol. 20, p. ES6011.
https://doi.org/10.2205/2020ES000720

Bloshkina, E.V. and Ivanov, V.V., Convective structures in the Norwegian and Greenland seas according to the results of modeling with high spatial resolution, *Tr. Gidrometeorol. Nauchno-Issled. Tsentra Ross. Fed.*, 2016, no. 361, pp. 146–168.

Fedorov, A.M., Bashmachnikov, I.L., and Belonenko, T.V., Localization of deep convection areas in the Nordic seas, the Labrador Sea and the Irminger Sea, *Vestn. S.-Peterb. Univ., Nauki Zemle*, 2018, vol. 63, no. 3, pp. 345–362.
https://doi.org/10.21638/spbu07.2018.306

Fedorov, A.M., Bashmachnikov, I.L., and Belonenko, T.V., Winter convection in the Lofoten Basin according to ARGO buoys and hydrodynamic modeling, *Vestn. S.-Peterb. Univ., Nauki Zemle*, 2019, vol. 64, no. 3, pp. 491–511.
https://doi.org/10.21638/spbu07.2019.308

Fedorov, A.M., Raj, R.P., Belonenko, T.V., Novoselova, E.V., Bashmachnikov, I.L., Johannessen, J.A., and Pettersson, L.H., Extreme convective events in the Lofoten Basin, *Pure Appl. Geophys.*, 2021, no. 178, pp. 2379–2391.
https://doi.org/10.1007/s00024-021-02749-4

Hausmann, U., Czaja, A., and Marshall, J., Mechanisms controlling the SST air–sea heat flux feedback and its dependence on spatial scale, *Clim. Dyn.*, 2017, no. 48, pp. 1297–1307.
https://doi.org/10.1007/s00382-016-3142-3

Isachsen, P.E., Mauritzen, C., and Svendsen, H., Dense water formation in the Nordic seas diagnosed from sea surface buoyancy fluxes, *Deep Sea Res.*, 2007, no. 54, pp. 22–41.

Kara, A.B., Rochford, P.A., and Hurlburt, H.E., An optimal definition for ocean mixed layer depth, *J. Geophys. Res.*, 2000, vol. 105, no. C7, pp. 16803–16821.

Kubryakov, A.A., Belonenko, T.V., and Stanichnyi, S.V., Impact of the synoptic eddies on SST in the northern part of the Pacific Ocean, *Sovrem. Probl. Distantsionnogo Zondirovaniya Zemli Kosmosa*, 2016, vol. 13, no. 2, pp. 124–133.
https://doi.org/10.21046/2070-7401-2016-13-2-34-43

Lappo, S.S., Gulev, S.K., and Rozhdestvenskii, A.E., *Krupnomasshtabnoe teplovoe vzaimodeistvie v sisteme okean–atmosfera i energoaktivnye oblasti Mirovogo okeana* (Large-Scale Thermal Interaction in the Ocean–Atmosphere System and Energy-Active Regions of the World Ocean), Leningrad: Gidrometeoizdat. 1990.

Malinin, V.N. and Shmakova, V.Yu., Variability of energy-active zones in the North Atlantic, *Fundam. Prikl. Klimatol.*, 2018, vol. 4, pp. 55–70.

Mikaelyan, A.S., Zatsepin, A.G., and Kubryakov, A.A., Effect of mesoscale eddy dynamics on bioproductivity of marine ecosystems (review), *Mors. Gidrofiz. Zh.*, 2020, vol. 36, no. 6, pp. 646–675.
https://doi.org/10.22449/0233-7584-2020-6-646-675

Novoselova, E.V., Seasonal variability of the potential vorticity in the Lofoten Vortex, *Russ. J. Earth Sci.*, 2022, vol. 22, no. 3, ES3006.

Novoselova, E.V. and Belonenko, T.V., Isopycnal advection in the Lofoten Basin of the Norwegian Sea, *Fundam. Prikl. Gidrofiz.*, 2020, vol. 13, no. 3, pp. 56–67.
https://doi.org/10.7868/S2073667320030041

Praveen Kumar, B., Vialard, J., Lengaigne, M., Murty, V.S.N., and McPhaden, M.J., TropFlux: Air–sea fluxes for the global tropical oceans: Description and evaluation, *Clim. Dyn.*, 2011, no. 38, pp. 1521–1543.
https://doi.org/10.1007/s00382-011-1115-0

Raj, R.P., Chafik, L., Nilsen, J.E.O., Eldevik, T., and Halo, I., The Lofoten vortex of the Nordic seas, *Deep-Sea Res. I*, 2015, vol. 96, pp. 1–14.
https://doi.org/10.1016/j.dsr.2014.10.011

Richards, C.G. and Straneo, F., Observations of water mass transformation and eddies in the Lofoten Basin of the Nordic seas, *J. Phys. Oceanogr.*, 2015, vol. 45, no. 6, pp. 1735–1756.
https://doi.org/10.1175/jpo-d-14-0238.1

Sandalyuk, N.V., Bosse, A., and Belonenko, T.V., The 3D structure of mesoscale eddies in the Lofoten Basin of the Norwegian Sea: A composite analysis from altimetry and in situ data, *J. Geophys. Res.: Oceans*, 2020, no. 125, e2020-JC016331.
https://doi.org/10.1029/2020JC016331

Schneider, N. and Qiu, B., The atmospheric response to weak sea surface temperature fronts, *J. Atmos. Sci.*, 2015, vol. 72, no. 9, pp. 3356–3377.
https://doi.org/10.1175/JAS-D-14-0212.1

Small, R.J., Bryan, F.O., Bishop, S.P., and Tomas, R.A., Air–sea turbulent heat fluxes in climate models and observational analyses: What drives their variability?, *J. Clim.*, 2019, vol. 32, pp. 2397–2421.
https://doi.org/10.1175/JCLI-D-18-0576.1

Søiland, H., Chafik, L., and Rossby, T., On the long-term stability of the Lofoten Basin eddy, *J. Geophys. Res.: Oceans*, 2016, no. 121, pp. 4438–4449.
https://doi.org/10.1002/2016JC011726

Sun, X. and Wu, R., Spatial scale dependence of the relationship between turbulent surface heat flux and SST, *Clim. Dyn.*, 2022, vol. 58, pp. 1127–1145.
https://doi.org/10.1007/s00382-021-05957-9

Timonov, V.V., Smirnova, A.I., and Nepop, K.I., Centers of the ocean–atmosphere interaction in the North Atlantic, *Okeanologiya*, 1970, vol. 10, no. 5, pp. 745–749.

Travkin, V.S. and Belonenko, T.V., Seasonal variability of mesoscale eddies of the Lofoten Basin using satellite and model data, *Russ. J. Earth Sci.*, 2019, vol. 19, no. 5, ES5004.
https://doi.org/10.2205/2019ES000676

Travkin, V.S. and Belonenko, T.V., Mixed layer depth in winter convection in the Lofoten Basin in the Norwegian Sea and assessment methods, *Gidrometeorol. Ekol. (Uch. Zap. RGGMU)*, 2020, vol. 59, pp. 67–83.
https://doi.org/10.33933/2074-2762-2020-59-67-83

Travkin, V.S. and Belonenko, T.V., Study of the mechanisms of vortex variability in the Lofoten Basin based on energy analysis, *Phys. Oceanogr.*, 2021, vol. 28, no. 3, pp. 294–308.
https://doi.org/10.22449/1573-160X-2021-3-294-308

Volkov, D.L., Kubryakov, A.A., and Lumpkin, R., Formation and variability of the Lofoten Basin vortex in a high-resolution ocean model, *Deep Sea Res.*, 2015, vol. 105, pp. 142–157.
https://doi.org/10.1016/j.dsr.2015.09.001

Yu, L.-S., Bosse, A., Fer, I., Orvik, K.A., Bruvik, E.M., Hessevik, I., and Kvalsund, K., The Lofoten Basin eddy: Three years of evolution as observed by Seagliders, *J. Geophys. Res. Oceans*, 2017, no. 122, pp. 6814–6834.
https://doi.org/doi:10.1002/2017JC012982.