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HOW MUCH LESS OXYGEN CAN THE WARMING CASPIAN SEA HOLD? THE LOSS OF OXYGEN SOLUBILITY IN THE NORTHERN, MIDDLE AND SOUTHERN CASPIAN, 1982-2022

Abstract: Warming lowers the amount of oxygen that sea water can hold, even if nothing else changes. Using April-October sea-surface temperature from two satellite-based records, OISST v2 and Pathfinder, both based mainly on the AVHRR instruments, this study estimates this warming-only loss of equilibrium oxygen solubility in the three basins of the Caspian Sea over 1982-2022; the northern winter, with no measured OISST temperatures under the ice, is left out. Solubility fell by 5.8%, 3.6% and 3.3% in the north, middle and south in OISST and by 3.8%, 3.4% and 2.6% in Pathfinder. The two records agree in the middle basin, differ slightly in the south and clearly in the north, where the spring is doubtful in both. The northern loss is significantly larger than the southern one only when April, the month with ice in OISST and with the most doubtful Pathfinder values, is included, and even then not in the full Pathfinder record, so the author's hypothesis that the north loses more is not robustly supported. Over 1982-2022, in both records, in every basin and in the three seasons compared (April-October, May-October, June-October), the loss was faster in 1982-2001 than in 2002-2022, but significantly so only in single basins and seasons, never in the same ones in both records, so a departure from a steady loss is not established. The result is the equilibrium level that warming has lowered; measured upper-layer oxygen lies at 69-109% of it off the Iranian coast (117% for one doubtful value) and, in one 2009 study in the north-east that could not be checked, at 125-175%.

Keywords: Caspian Sea, dissolved oxygen, oxygen solubility, sea-surface temperature, climate warming, satellite data, OISST, AVHRR Pathfinder

Introduction

My city, Atyrau, stands on the Ural River, and it is the northern Caspian that the Ural flows into. For a long time I have seen the river grow shallower with my own eyes, and this gave me a personal reason to be interested: to learn more about what can be seen with the eyes (the retreating water) and what cannot be seen (the fall in oxygen solubility). Before any results of this study were calculated, on 22 September, I wrote that in my opinion the loss of oxygen solubility would be larger in the north than in the south. First, the north is shallow, so it warms up faster. Second, the colder the water, the more strongly each degree of warming acts on it, and the north is exactly the part of the Caspian that is colder than the others.

Oxygen dissolves less in warm water than in cold water, so a warming sea loses oxygen even if biology and circulation stay the same. Warming of the ocean and the stronger stratification of its upper layer that comes with it are expected to lower the oxygen of the

ocean interior [1], and the global ocean has lost more than 2% of its oxygen in fifty years [2]. Lakes are losing oxygen too: a model-based reconstruction of surface oxygen in 15,535 lakes for 2003-2023 found a mean loss of 0.049 mg/L per decade and attributed 55% of it to lower solubility caused by climatic warming [3].

The Caspian Sea is the largest lake on Earth and consists of three different basins [4]. The northern basin is at most 25 m deep and shallower than 5 m over about two-thirds of its area; it holds only 0.5% of the volume of the sea, while the deep middle and southern basins hold 33.9% and 65.6% [4]. The most important rivers enter on the northern and western coasts, and the average salinity is 9.28‰ in the northern basin, 13‰ in the middle basin and 13.1‰ in the southern basin [4]. In the north, winter generally lasts from December to March, and sea ice covers the shallow north out to about the 12 m depth contour [4]. The level of the Caspian fell from 1996 to at least 2015, mainly because evaporation over the sea increased [5], and climate models project a further decline by the end of the century of about 8 m (inter-model range 2-15 m) under the SSP245 scenario and 14 m (11-21 m) under SSP585, which would dry out the northern basin completely [6]. The surface of the Caspian warmed by +0.24 °C per decade over 1982-2022, about 2.2 times the global-ocean rate, in an estimate that used all twelve months, including the northern winter [7]; without the northern December-March values the same record and cells give 0.31 °C per decade (recalculated in this study).

Oxygen in the Caspian has been measured at sea. Near the Iranian coast, CTD surveys in 2004-2005 measured upper-layer oxygen between 69% and 109% (117% for one doubtful value) of the equilibrium calculated here [8] (see Results). In the deep southern basin the low-oxygen conditions are getting stronger, oxygen near the bottom is close to zero, and winter mixing had not reached the bottom at the time of the survey [9]. This deep loss is a different process from the solubility effect studied here. In the literature read for this study, no estimate was found of how much oxygen the warming of the satellite era alone has taken from the surface water of each basin. This study asks three questions. By how many per cent did the oxygen solubility of the Caspian surface fall from 1982 to 2022 because of warming? Did this loss proceed steadily or in jumps? Did the north lose more than the south? The author's hypothesis was that it did. Asked how much less oxygen the water would hold after warming by 1 °C, the author predicted about 2.3% in the north and 2.0% in the south. In his words, translated from Russian: "the colder the water, the more strongly each additional degree acts on it", and the curve of solubility against temperature "will be convex".

Materials and methods

Temperature data. As in [7], monthly sea-surface temperature (SST) came from version 2 of the NOAA Optimum Interpolation analysis (OISST v2), which combines satellite and ship and buoy measurements on a 1° grid [10]. All 492 months of 1982-2022 were read. The Caspian cells are the water cells of the dataset's land-sea mask inside 36-48° N and 46-55° E, the 57 cells of [7], minus the four cells over and next to the hypersaline Kara-Bogaz-Gol lagoon (40.5-41.5° N, 53.5-54.5° E), a choice made after the first results; 53 cells remain. They were divided into basins by the latitude of the cell centre: north at 45.5° N and above (12 cells), middle from 40.5° to 44.5° N (24 cells) and south at 39.5° N and below (17 cells). These bands only approximate the real basins: by area they hold 21%, 45% and 34% of the cells, while the three basins cover 24%, 36% and 39% of the sea [4], so parts of the northern and southern basins fall into the middle band. Basin means were weighted by the cosine of latitude.

The season used. In ice-covered water OISST v2 has no measured temperatures: the analysis converts sea-ice concentration of at least 15% into a proxy SST [10, p. 1618], and when the product was described in 2002 the Caspian sea ice came from a climatology, because none of its ice datasets covered the Caspian [10]. The main analysis therefore uses April to October, a season chosen after the all-month results of [7] were known and before the ice field of the dataset was read, which leaves out the northern winter of December to March [4] and November. This is meant to avoid the ice proxy but does not avoid it completely: in the ice field of the same dataset, the seven northern cells that have an ice value in every month of 1982-1998 carry a seven-cell mean, over 1982-2022, of 5.2% ice in April (the highest yearly seven-cell mean is 15.3%, in 1983, 1988, 1991 and 1996) and 0.6% in November (at most 11.1%), and 24 northern cell-months, all in April, of April-October reach the 15% threshold of the proxy. For each year the OISST solubility was calculated for every cell and month and averaged over the season. The calculation was repeated for April-November, May-October and June-October.

Solubility. The equilibrium solubility of oxygen in water in contact with air at one atmosphere was calculated with the TEOS-10 function gsw_O2sol_SP_pt [11], which implements the Garcia and Gordon fit, in µmol/kg ([12], cited via [11], because the paper itself could not be accessed). The coefficients used are identical to those in the TEOS-10 source code, and the implementation, reimplemented here from the TEOS-10 source, reproduces the TEOS-10 reference values to within about 0.01%; it omits the TEOS-10 conversion of temperature to the 1968 scale (a factor of 1.00024), which is the source of that difference. Salinity was held constant in time at the basin values of [4]: 9.28 for the north, 13.0 for the middle and 13.1 for the south. The source prints the unit as "percent", but the values are parts per thousand (it gives the average salinity of the whole sea as 12.80-12.85), and they were used as practical salinity, which the equation expects; the two scales are close but not identical for Caspian water. With salinity fixed, every change in solubility comes from temperature alone, which is the warming-only loss the question asks about. For comparison with measurements, solubility was converted to mg/L with a water density of 1.005 kg/L (an error below 1%).

Loss per degree. The loss caused by +1 °C was calculated as the solubility at T − 0.5 °C minus the solubility at T + 0.5 °C, divided by the solubility at T, at the mean April-October temperature of each basin, at the mean temperature of all months, and averaged over the months, each at its own mean temperature.

Trend. The trend of the seasonal mean solubility was estimated by ordinary least squares on the annual values (41 in OISST), with Newey-West standard errors (three lags; twelve lags for the monthly all-month series) for all confidence intervals and p-values unless they are marked "ordinary"; ordinary 95% intervals of the solubility trends differ from the Newey-West ones by at most 0.11% per decade for the 1982-2022 trends. The trends were also checked with the non-parametric Theil-Sen slope. The change over the period is the trend multiplied by the 40 years from 1982 to 2022, relative to the mean solubility of the period; the change between the means of 1982-1986 and 2018-2022 is also given. Differences between basins were tested as the trend of the year-by-year difference of their per cent series (in percentage points, written % per decade); the halves test below was not run for April-November.

Steady or in jumps. First, separate trends were fitted to 1982-2001 and 2002-2022 in one regression; because the residuals are hardly autocorrelated (lag-one correlation 0.08 or less in OISST) and the series are short, ordinary p-values are given beside the Newey-West ones, and the conclusions rest on them, because they are the larger ones here. Second, a continuous line bending in 2002 was fitted. Third, the Pettitt test was applied to the residuals from the linear trend. Fourth, five models were compared with the Bayesian information criterion (BIC): a straight line (3 parameters including the error variance), a line bending in 2002 (4), two constant levels with a break (4, the break year counted), a broken line with a searched bend (5) and a straight line with a step (5). Break years were searched between 1987 and 2017 (1987-2012 for the Pathfinder north, which has gaps), with no correction for the search; a model is taken as clearly better only if its BIC is lower by more than 2. No correction was made for the number of tests, so single p-values near 0.05 are only suggestive.

Second satellite record. The calculation was repeated with the AVHRR Pathfinder version 5.3 monthly daytime composites at 4 km [13], from the NOAA CoastWatch ERDDAP server, whose monthly composite keeps only the highest-quality values of this skin temperature [14]. OISST and Pathfinder both rest mainly on the AVHRR instruments [10, 13] but are processed separately, so Pathfinder is a second, separately processed record of the same measurements. Points were taken every 0.25° inside the same 53 cells. Because clouds leave gaps, each point was expressed as an anomaly from its own 1991-2020 monthly mean (used only if it rests on at least 10 values); the basin temperature of a month is the basin mean of these point means plus the mean anomaly of the points with a value (at least 20% of the points), solubility was calculated from it (for OISST cell by cell, before averaging), and a year was used only when all months of the season were available; the northern Pathfinder series lacks a complete April-October season in 2011, 2013, 2016, 2017, 2019 and 2020. The main Pathfinder results are for 1982-2022; the period 1982-2020 and the omission of the four years with implausibly warm northern Pathfinder Aprils are sensitivity checks chosen after seeing the data (see Results); the omission of the four Aprils was not tested for the halves and the BIC models. For every result that uses the gapped northern Pathfinder series, ordinary p-values and intervals are given, because Newey-West lags would join years that are not neighbours (the middle basin lacks only 1995, a single gap accepted as negligible). The two records were compared by the trend of the year-by-year difference of their per cent series in the common years. Whole-sea values are weighted by cell area (OISST by cell, 41 years; Pathfinder as the area-weighted mean of the basin per cent series, 34 years).

Other checks. The OISST calculation was repeated with salinity 3 units lower and higher, with the Kara-Bogaz-Gol cells, without the spring cell-months below 2 °C, without the eruption year and the two years after for El Chichón (1982-1984) and Pinatubo (1991-1993) and without the three coldest northern years after removing the trend (1985, 1987, 1992). The larger northern loss in OISST was split on a logarithmic scale into faster warming, the lower mean temperature and the timing of the warming within the season (monthly loss per degree times monthly warming).

Comparison with measured oxygen. Published measurements of dissolved oxygen were compared with the solubility calculated for the reported temperature and the reported or, where not reported, assumed salinity: four CTD surveys off the Iranian coast in 2004-2005 [8] and measurements from the shallow north-eastern Caspian in summer and autumn 2009 [15].

Reproducibility and ethics. Only openly available environmental data were used; there were no human or animal subjects. The code and all results are kept, and the data are public.

Results

One degree of warming. For April-October, +1 °C removes 1.96% of the solubility in the north (mean 19.0 °C), 1.93% in the middle and 1.84% in the south (Table 1); averaged month by month the values are almost the same (1.98%, 1.94% and 1.85%). The prediction of 2.3% and 2.0% is higher by 0.34 and 0.16 percentage points, and its order, north above south, is right. Over all months the values are 2.19%, 2.08% and 1.96% at the mean temperature and 2.24%, 2.11% and 1.98% averaged month by month; the prediction, which was not tied to a season, is within 0.02-0.11 points of these, but the northern all-month values include the winter proxy values. The convexity of the solubility curve explains why cold water loses more milligrams per degree; the larger loss in per cent follows from the relative slope of the curve, which is also steeper in cold water. In April-October the north is 3.2 °C colder than the south (19.02 against 22.25 °C) in OISST and slightly colder than the middle (19.4 °C); in Pathfinder it is warmer than the middle (20.1 against 19.6 °C).

Table 1. Loss of oxygen solubility caused by +1 °C: the author's prediction and the equation (temperatures from OISST v2; practical salinity)

Basin	Salinity	Predicted, % per °C	Apr-Oct: T, °C	Apr-Oct: % per °C	All months: T, °C	All months: % per °C
North	9.28	2.3	19.0	1.96	12.5	2.19
Middle	13.0	not given	19.4	1.93	14.9	2.08
South	13.1	2.0	22.3	1.84	18.4	1.96

How much was lost. All three basins lost solubility in both records and every season (Tables 2 and 3). In OISST the north warmed fastest in April-October, by 0.67 °C per decade, and its solubility fell by 1.46% per decade, or 5.8% over the 40 years (95% CI 4.2-7.4%). The middle and south warmed by 0.46 °C per decade and lost 0.90% and 0.83% per decade, or 3.6% and 3.3%. The three April-October OISST trends are significant ($p < 0.001$). The Theil-Sen slopes are 1.19, 0.80 and 0.80% per decade (4.8% over 40 years in the north). Between 1982-1986 and 2018-2022 the mean solubility fell by 4.3%, 2.7% and 2.7%, less than the trend gives, partly because the centres of the two five-year windows are 36 years apart. For the whole sea, the April-October loss is 4.0% in OISST.

Pathfinder follows OISST closely in the middle and south (correlation of the annual values 0.94 and 0.90; 0.87 and 0.85 after removing the trends) and less closely in the north (0.71; 0.55 after removing the trend). Over 1982-2022 it loses 0.95%, 0.86% and 0.64% per decade in the north, middle and south, or 3.8%, 3.4% and 2.6% (Table 2), and 3.5% for the whole sea. The trend of the difference between the records (OISST minus Pathfinder) is −0.63% per decade in the north (ordinary $p = 0.011$), −0.06% in the middle ($p = 0.34$) and −0.18% in the south ($p = 0.029$): the records agree in the middle, differ slightly in the south and clearly in the north. Relative to the mean of the common years, Pathfinder minus OISST in the north varies from −1.0 to +1.7 °C before 2021 and is −1.3 and −1.6 °C in 2021 and 2022, colder relative to OISST than in any earlier year; in the middle and south the 2021-2022 values stay within the earlier range. The sources read do not document a cause. As sensitivity checks, the records were also compared over 1982-2020 and without the four years whose

northern Pathfinder April mean was 15.7-19.2 °C, far above every other year (at most 13.8 °C): 1995, 2012, 2014 and 2015, three of them with an April value at only 31-38% of the points, removed from both records (Table 3). Over 1982-2020 the northern difference between the records is not significant (−0.41% per decade, ordinary p = 0.13); without the four years, Pathfinder gives 3.1% for the north over 1982-2022.

Table 2. April-October trends in the two satellite records, 1982-2022 (OISST v2, Pathfinder v5.3; 95% confidence intervals in brackets, Newey-West, ordinary for the gapped Pathfinder north)

Basin	OISST warming, °C per decade	OISST solubility, % per decade	Pathfinder warming, °C per decade	Pathfinder solubility, % per decade	Pathfinder years
North	+0.67 (0.51, 0.83)	−1.46 (−1.86, −1.06)	+0.46 (0.21, 0.71)	−0.95 (−1.48, −0.42)	35
Middle	+0.46 (0.35, 0.57)	−0.90 (−1.11, −0.69)	+0.44 (0.31, 0.58)	−0.86 (−1.10, −0.61)	40
South	+0.46 (0.36, 0.56)	−0.83 (−1.01, −0.65)	+0.35 (0.24, 0.46)	−0.64 (−0.84, −0.45)	41

Table 3. Change in solubility, %, by season and record (trend × 40; last two columns: post-hoc sensitivity checks, both records in the Pathfinder years of each basin, the four years removed in every basin; Pathfinder north: 35, 33, 38, 39, 33 and 29 years)

Basin and record	Apr-Oct	Apr-Nov	May-Oct	Jun-Oct	Apr-Oct, 1982-2020 trend × 40	1982-2020, without 4 warm Aprils
North, OISST	−5.8	−4.1	−4.4	−2.8	−6.7	−7.5
North, Pathfinder	−3.8	−3.4	−2.9	−2.6	−5.1	−4.4
Middle, OISST	−3.6	−3.4	−3.6	−3.4	−3.8	−3.8
Middle, Pathfinder	−3.4	−3.3	−3.4	−3.3	−3.7	−3.6
South, OISST	−3.3	−2.9	−3.6	−3.5	−3.4	−3.3
South, Pathfinder	−2.6	−2.3	−2.4	−2.3	−2.8	−2.7

Does the north lose more than the south? For April-October the north loses more than the south in OISST (by 0.63% per decade; ordinary p = 0.001, Newey-West 0.003; over 1982-2020 ordinary p = 0.001). In Pathfinder the difference is not significant over 1982-2022 (ordinary p = 0.21); in the 1982-2020 sensitivity check it is suggestive (ordinary p = 0.043) but disappears without the four warm Aprils (1982-2020, ordinary p = 0.19). For April-November only one of the two OISST tests is below 0.05 (ordinary p = 0.049, Newey-West 0.14), and in Pathfinder ordinary p is 0.11. For May-October and June-October the difference is not significant in either record (ordinary p from 0.15 to 0.77); in OISST for June-October the north even loses less. Over 1993-2022, after the step in the northern OISST series, the OISST April-October north-minus-south difference is not significant either (the north loses 0.17% per decade more, Newey-West p = 0.35). The extra northern warming in OISST is largest in April and May (+1.02 and +0.85 °C per decade more than in the south): without April the northern excess shrinks to 0.20% per decade (not significant), and without April and

May it reverses. On a logarithmic scale the OISST north-to-south loss ratio (1.8) splits into faster warming (about 65%), the lower mean temperature (about 11%, with the lower salinity), the timing of the warming (about 10%) and a remainder (about 14%), part of it the extra weight of the strongly warming spring months, when solubility is high. The north warmed faster than the south in OISST (by 0.21 °C per decade, p = 0.014) but not significantly in Pathfinder (0.09, ordinary p = 0.34), where it warmed as fast as the middle (trend of the difference in the 34 common years 0.00).

Steady or in jumps. In OISST the loss was faster in 1982-2001 than in 2002-2022 (Table 4): 2.14% against 0.48% per decade in the north, 1.48% against 0.46% in the middle and 1.27% against 0.82% in the south. With ordinary p-values (the residuals are hardly autocorrelated), the difference holds in the north (0.027; 0.002 and 0.032 in the two leave-out checks), only marginally in the middle (0.046; 0.052 and 0.070; Newey-West 0.004, 0.003 and 0.012) and not in the south (0.38). The line bending in 2002 is not clearly better than a straight line (Table 5: a margin of 2.0 in the north, at the threshold, and 0.7 in the middle). For the northern OISST series a straight line with a drop of about 2.4% in 1993 has the lowest BIC (117.7, with the year searched), clearly better than the straight line, though not than the bend; a run of nine cold OISST Aprils (2.8-6.1 °C, 1984-1992) ends in 1993, after which only 1996 and 2003 fall in that range, and with this step in the model the bend at 2002 disappears (slope change −0.12% per decade, p = 0.90). In the middle the line with a step ties with the straight line, and in the south the straight line is best. In Pathfinder the northern April-October pattern is not significant. Over 1982-2022 its first half is faster in all three basins (ordinary p = 0.55, 0.19 and 0.52); in the 1982-2020 check the first half is slower in the north for April-October and in the south for May-October (ordinary p = 0.37 and 0.92). For June-October its first half is faster in the north and middle (ordinary p = 0.009 and 0.029; 0.053 and 0.08 in the 1982-2020 check). In the full Pathfinder record the straight line is best in the north and south, and the middle is better described by two constant levels with a break around 1998 (BIC 87.2 against 92.3, with the year searched); the Pettitt test finds no abrupt shift in any basin of either record (p from 0.14 to > 0.5), though it has little power on detrended residuals. So over 1982-2022, in both records, in every basin and in the three seasons April-October, May-October and June-October, the loss was faster in 1982-2001, but significantly so only in single cases (also OISST north for May-October, ordinary p = 0.018), never in the same basin and season in both records.

Table 4. Change in solubility in the two halves of the period (April-October, OISST v2; slowdown with its Newey-West 95% CI; conclusions use ordinary p)

Basin	1982-2001, % per decade	2002-2022, % per decade	Slowdown, second minus first half	p, ordinary / Newey-West
North	−2.14	−0.48	1.66 (0.43, 2.89)	0.027 / 0.008
Middle	−1.48	−0.46	1.02 (0.33, 1.71)	0.046 / 0.004
South	−1.27	−0.82	0.45 (−0.25, 1.14)	0.38 / 0.21

Table 5. Model comparison by BIC (April-October, OISST v2; lower is better, a difference above 2 counts)

Basin	Straight line	Line bending in 2002	Two levels	Broken line	Line with a step
North	121.5	119.5	122.6	121.9	117.7
Middle	86.0	85.4	87.9	87.9	86.0
South	79.8	82.8	86.9	86.0	83.8

The northern records. Over all twelve months the north shows no significant change in OISST (+0.33% per decade, 95% CI from −0.26 to +0.93), while the middle and south lose 0.72% and 0.55%, because OISST cools the northern winter by 1.57, 1.45 and 0.87 °C per decade in December, January and February (no Pathfinder data). The ice field of the northern cells changes in the early 2000s. In 1982-1997 the seven-cell mean ice concentration repeats in an eight-year cycle (the December-April values of 1990-1997 repeat those of 1982-1989); after a transition in 1998-2003, in which the January values (and from 1999 the December values) leave the cycle and rise year by year, the values vary from year to year from 2004, although some April cycle values still recur. On the seven cells that have a value in every month of 1982-1998, the mean ice concentration in 1982-2003 and 2004-2022 is 1.0% and 20.5% in December, 73.0% and 39.7% in March and 7.7% and 2.3% in April. The northern winter values are probably a data artefact, but the mechanism is not established. The ice field and the SST do not always match either: in March 1982, 1983, 1993 and 1994 the seven cells carry 72-74% ice while the twelve northern cells have a mean SST of 6.8-8.7 °C. In 1985-1992 the northern Pathfinder Aprils are 4-10 °C warmer than OISST in most years (1984 agrees), and after 1999 the OISST Aprils are mostly 8-11 °C; the same April ice values recur in the warm Aprils of 1993 and 1994, so the ice field does not explain this. Pathfinder's northern spring has problems of its own: its April means are 18.6, 15.7, 17.6 and 19.2 °C in 1995, 2012, 2014 and 2015, against at most 13.8 °C in every other year and 7.7-9.2 °C in OISST in the same years; without these four years Pathfinder's northern loss over 1982-2022 is 0.78% per decade (ordinary 95% CI 0.29-1.26) instead of 0.95%. Removing the 10 spring cell-months below 2 °C changes OISST little (1.43% per decade). By month, the April trends of the two records agree roughly but differ in May and June (Table 6), also in the 1982-2020 check. Neither record can be preferred for the northern spring.

Table 6. Northern basin: SST trend by month, °C per decade, 1982-2022 (December-February: see text; Pathfinder: 33-41 years per month)

Record	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
OISST v2	+0.14	+1.24	+1.39	+1.13	+0.51	+0.41	+0.17	−0.16	−0.55
Pathfinder v5.3	+1.79	+0.95	+0.38	+0.43	+0.30	+0.48	+0.33	+0.20	+0.33

Robustness. With salinity 3 units lower or higher, the trends change by less than 0.02% per decade; with the northern salinity at 4.5 or 6.0, close to the World Ocean Atlas values of 4.79-7.51 at a northern point [16], the northern OISST loss is 1.48% and 1.47% per decade instead of 1.46%. With the Kara-Bogaz-Gol cells included, the middle basin loses 0.78% per decade (3.1% over 40 years) instead of 0.90% (3.6%).

Comparison with measured oxygen. Off the Iranian coast, measured oxygen ranged from 69-75% of the calculated equilibrium at the shelf minimum in April 2004 to 104-109%

in the cold, well-mixed upper 100 m in February 2005 and 90-117% above the thermocline in May 2005 (Table 7) [8]; the 117% rests on the value of 10.5 mg/L, which [8] prints as 96% saturation, so it may come from colder water. The saturation percentages printed in [8] were not used, because several do not fit its concentrations (for February 2005, 10.9 mg/L is given as 92% and 11.2 mg/L as 108%); only the concentrations, temperatures and salinities of [8] were used. For October 2004 the temperature above the thermocline (19-21 °C) was used for both rows, also for the shelf, for which [8] gives no temperature, with salinity 12.35 outside the shelf and 11.65-12.35 over it; for February 2005 the mixed-layer values of 9.5-10.5 °C and 12.3-12.35 were used. For April 2004 ([8]: upper 30 m "below 12", 14 °C at 0-10 m and 12 °C at 10-30 m) 10-12.3 and 11-14 °C were assumed, and for May 2005 ([8]: "mainly less than 12" over the shelf, 12.3-12.4 outside) 11-12.4. In the shallow north-eastern Caspian, water 1.5-3 m deep held 10.6-12.8 mg/L in summer 2009 at 27-29 °C [15]; station by station this is 134-175% of the equilibrium amount. In autumn 2009, at 20-21 °C, it was 125-143% [15]. The study [15] reports chloride but not salinity and does not state how or at what depth oxygen was measured, so the percentages were calculated station by station, each at its own temperature, for every salinity from 0 to 9.28; its measurements could not be checked.

Table 7. Measured dissolved oxygen and calculated equilibrium solubility (temperature and salinity as reported, or assumed as stated in the text; for [15] station by station)

Place and time	T, °C	Measured oxygen, mg/L	Calculated solubility, mg/L	Measured, % of solubility
South, 0-40 m off the shelf, Apr 2004 [8]	11-14	8.3-9.2	9.5-10.3	80-97
South, shelf minimum, Apr 2004 [8]	11-14	7.1	9.5-10.3	69-75
South, 0-30 m off the shelf, Oct 2004 [8]	19-21	7.6	8.3-8.6	88-92
South, shelf maximum, Oct 2004 [8]	19-21	8.8	8.3-8.6	102-106
South, upper 100 m, Feb 2005 [8]	9.5-10.5	10.9-11.2	10.3-10.5	104-109
South, above thermocline, May 2005 [8]	17	8.1-10.5	8.9-9.0	90-117
North-east, summer 2009 [15]	27.0-29.2	10.6-12.8	7.3-8.0	134-175
North-east, autumn 2009 [15]	20.3-21.0	11.2-12.1	8.4-9.1	125-143

Discussion

The northern loss depends on the record (3.8% or 5.8% over 1982-2022; the difference is not significant over 1982-2020 and larger without the four warm Aprils, Table 3) and on the season (2.6-4.4% for the other seasons), because much of the northern warming falls in April and May in OISST and in April in Pathfinder.

The author's hypothesis that the north loses more than the south is not robustly supported. In OISST the north loses more for April-October. In Pathfinder the difference is only suggestive, in a sensitivity check, and disappears without the four warm Aprils. The difference is significant in OISST, and suggestive in Pathfinder, only when April is included,

and over 1993-2022, after the northern OISST step, it is not significant in OISST either. May and June also differ between the records. The first part of his reasoning, that the north warms faster, holds in OISST but not significantly in Pathfinder; depth itself was not tested. His reasoning that cold water loses more per degree holds against the south, which is warmer in both records (in Pathfinder the north is warmer than the middle); in OISST this explains about 11% of the north-south ratio, including the lower northern salinity. His prediction of the loss per degree has the right order and is somewhat higher than the April-October values of the equation.

For April-October, departures from a steady loss appear in one record only: in the northern OISST series (a faster early loss and a 1993 step), marginally in the OISST middle basin (a faster early loss) and in the Pathfinder middle basin (a level shift around 1998). None is significant in the other record. The author's earlier study found faster warming in the first half of the record (+0.43 against +0.09 °C per decade, all months) [7]; the same split, reconstructed here without the northern December-March values, gives +0.55 against +0.10, which, from the same record, is not independent support.

The author's own explanation of the faster early loss in the point estimates (Table 4), written on 25 October in answer to the mentor's question and translated close to his Russian text: "In 1982-2001 the temperature was lower, and from 2002 to the present it is already higher (the water has had time to warm). Even at the same rate of temperature rise, the percentage loss of solubility will be larger in the cold period than in the warm one, just as on the convex line [the curve of solubility against temperature, discussed with his mentor] on the graph we talked about."

This explanation was tested. In the northern OISST series the mean April-October temperature was 18.3 °C in 1982-2001 and 19.7 °C in 2002-2022, so one degree removed 1.98% and 1.93% of the solubility. The direction is the one the author gives (strictly, it follows from the relative slope of the curve, which is steeper in cold water, rather than from its convexity), but at the same warming rate it accounts for only about 2% of the difference between the halves (0.03 of 1.62% per decade, each half relative to its own mean; 1.66 in Table 4, relative to the whole-period mean; 1-3% in every basin and in both records). Most of the difference comes from the faster warming of the first half (in the north 0.94 against 0.25 °C per decade, 1.36 of the 1.62); the remaining 0.23 is not attributed. In the northern OISST series the 1993 step describes this at least as well as a bend in 2002 (Table 5).

Off the Iranian coast, the measured upper-layer oxygen lay within about 20% of the calculated equilibrium, except the April 2004 shelf minimum (69-75%) [8]. This fits exchange with the air keeping the water near equilibrium, but four surveys on two transects, spread over about 48 percentage points, cannot show a southern shift of 2.3-3.6%. In the shallow north-east, [15] reports far more oxygen in summer 2009 than the equilibrium amount. The cause is presumably photosynthesis in such shallow water, an inference of this study that [15] does not discuss. The solubility calculated here is the equilibrium level towards which exchange with the air pulls the water; the deep southern water has lost oxygen for other reasons [8, 9].

In an experiment with juvenile beluga (Huso huso), the largest of the sturgeons, fish from the International Sturgeon Research Institute in Rasht were kept for eight weeks in tanks with 2-3, 5-6 or 9-10 mg/L of oxygen at 18 °C [17]. At the lowest level they ate less and grew more slowly, and fish in the larger weight group kept at 9-10 mg/L ended heavier than those at 5-6 mg/L. In the north the 1982-2022 April-October trend corresponds to a warm-season

equilibrium level roughly 0.5 mg/L lower in OISST (5.8% of about 8.9 mg/L) and 0.3 mg/L lower in Pathfinder (3.8%), far less than the steps between the tank levels; whether it makes low-oxygen episodes more frequent was not tested.

Limitations. Salinity was fixed at one value per basin from a reference work [4], although it varies with the season and near the river mouths; lower or higher salinity changed the trends very little. The Garcia and Gordon equation was fitted to ocean water, and the salt of the Caspian may differ in composition; this was not checked. The 1° OISST cells mix open and coastal water, the latitude bands do not match the basins exactly, the sea level rose in 1979-1995 and fell after 1996 [5], which, in this study's inference, has changed the mix of water and land in the shallow north, and for the Caspian OISST used average Northern-Hemisphere coefficients to convert ice concentration into temperature [10]. Both northern records have doubtful springs and the northern OISST winters are not used (see Results). Pathfinder is a daytime record, labelled a skin temperature [14], although in 2002 its algorithm was determined by regression against buoy data [10, p. 1622]. Only the surface is analysed, and the measured oxygen comes from two studies. The World Ocean Atlas climatology examined at two Caspian points [16] could not be used for oxygen: Fig. 4 of [16] plots both points on a 20-50 µmol/kg axis, implausibly low for surface water; its lower northern salinity was used only in the robustness check, as [4] reports that northern salinity falls sharply in summer.

Conclusion

Over 1982-2022 warming lowered the April-October oxygen solubility of the Caspian surface by 3.4-3.6% in the middle, where the two satellite-based records agree, by 2.6-3.3% in the south, where they differ slightly, and by 3.8-5.8% in the north, where they differ clearly (2.6-2.8% for June-October), and by 4.0% (OISST) and 3.5% (Pathfinder) for the whole sea. The north lost significantly more than the south only when the doubtful April is included, and not in the full Pathfinder record, so the author's hypothesis is not robustly supported; after the 1993 step, over 1993-2022, the OISST difference is not significant either. The author's prediction that one degree removes more solubility in the colder north than in the south has the right order, with values somewhat above the equation. For April-October, no departure from a steady loss is significant in both records. The author's explanation of the faster early loss, that colder water loses more per degree, has the right direction but accounts for only about 2% of it. The next step is to compare the equilibrium level with regular measurements from the Kazakh part of the northern Caspian whose method and depth are stated, for example national monitoring; a third temperature record would help for the northern spring.

Author contributions and use of AI tools. The author chose oxygen in the Caspian as the topic on 17 September 2026, from five directions proposed by his mentor in the ADMIT programme, who is not the scientific supervisor named above; the mentor had marked this direction as recommended. The mentor recalled that the author's first paper had shown about one degree of warming, told him that one degree removes about 2% of the solubility, and asked how much oxygen the Caspian had lost to warming and whether the loss is larger in the shallow north or the deep south (15 September, in the five-direction message; repeated on 17 September, when he also described the north as shallow and strongly warmed in summer); the mentor fixed the wording of the research question on 19 September and asked for the author's hypothesis. The author wrote the hypothesis that the north loses more than the south, and why (22 September). On 26 September the mentor accepted the hypothesis and called its physics

correct, writing that cold water loses more oxygen per degree and that the north is both shallower and colder. Asked how much less oxygen the water would hold after warming by 1 °C, the author answered 2.3% and 2.0% (18 October), after he had given this reason in his hypothesis (22 September) and the mentor had confirmed it (26 September), and while the calculation was still under way. He cited the sea-level studies [5, 6] in his own writing (21-24 September; [5] is also cited in [7]), found the studies of ocean and lake oxygen loss [2, 3] (5 October), the salinity values for the three basins [4] (8 October) and the beluga experiment [17] (10 October); on 27 September he sent short descriptions, without titles or links, of three studies of measured oxygen in the southern Caspian, one of which was identified as [9]; the other two could not be identified with certainty. He wrote the first paragraph of the Introduction in Russian (24 October, after the first results), and the mentor translated it into English with a generative AI tool (Claude, Anthropic), close to his words, placing his two sentences about Atyrau and the Ural first and adding, before his two reasons, a sentence framed by the mentor that gives his hypothesis of 22 September, translated, with its date. The mentor, working with the same tool, designed the method (the seasons, the basin boundaries, the exclusion of Kara-Bogaz-Gol and the statistical tests), wrote and ran the analysis code, made the tables, added the second satellite record, the ice check and the comparison with measured oxygen, found the other sources cited, including [8] and [15], and wrote the English text of every section except the first paragraph of the Introduction and the author's explanation in the Discussion, which he wrote in Russian (25 October, in answer to the mentor's question) and the mentor translated with the same tool, close to his words, and tested. Every number comes from the code's output, a cited source or the author's messages and was checked by the mentor. Of the cited works, [1], [2], [3], [5], [6] and [9] were read as abstracts only, and [12] is cited via [11]. The author read and approved the whole manuscript, including this section, before submission; the scientific supervisor took no part in the analysis or the writing.

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Data availability. OISST v2, including its ice concentration, is available from the NOAA Physical Sciences Laboratory (URL: https://downloads.psl.noaa.gov/Datasets/noaa.oisst.v2/), and AVHRR Pathfinder v5.3 from the NOAA CoastWatch ERDDAP server (dataset erdPH53sstdmday) [14]. The analysis code and its output, prepared by the mentor, are held by the author and available from him on request.

Conflict of interest. The author takes part in the ADMIT mentoring programme, a paid educational service, whose mentor carried out the analysis and wrote the text as described above. The author declares no other conflict of interest.

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