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Revisiting Koba's relationship to improve minimum sea-level pressure estimates of western North Pacific tropical cyclones

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Abstract

Currently, the Regional Specialized Meteorological Center Tokyo applies the satellite-based Dvorak technique using the relationship developed by Koba et al. (1990) for one of the important sources of tropical cyclone (TC) intensity analysis. To improve TC intensity analysis, we revisited Koba's relationship used for estimating the minimum sea level pressure (MSLP) considering case selection, aircraft data treatment, current intensity (CI) numbers, and additional explanatory variables. The root mean squared difference (RMSD) of the MSLP between the aircraft data and the concurrent estimates based on the original formula of Koba et al. (1990) is approximately 13.0 hPa. The RMSD reduced by 28% to 9.3 hPa in the revised regression model that used CI numbers analyzed through modern methods and additional explanatory parameters (development rate, size, latitude, and environmental pressure) with careful treatment of the aircraft data. The signs of the coefficients in the proposed model suggest that the actual MSLP change lags the change in the corresponding CI number. The large TC at high latitudes with lower environmental pressure has a low MSLP for a given CI number. Cross-validation results supported the superiority of the proposed model. The current approach is simple but substantially improves the quality of the TC intensity analysis, leading to improved TC forecasts through TC bogus, wave models, storm surge models, and forecast verification.

Keywords: tropical cyclones; Dvorak technique; historical dataset

1. Introduction

The estimation of tropical cyclone (TC) intensity parameters, such as the maximum sustained 10-meter wind speed (Vmax) and minimum sea-level pressure (MSLP), is essential for disaster prevention and mitigation. This is related to the severity of the disaster, preparedness of the people, and decision-making by the government. Currently, the Regional Specialized Meteorological Center (RSMC) Tokyo - Typhoon Center in JMA, issuing TC advisories in the Western North Pacific (WNP) within the framework of the World Weather Watch program of the World Meteorological Organization, applies the satellite-based Dvorak method (Dvorak 1975, 1984) using tables developed by Koba et al. (1990; hereafter K90)[1] as one of the important sources of TC intensity analysis, particularly for TCs in the open ocean. Satellite analysts at JMA examine satellite images and utilize the Dvorak Technique to derive a tropical (T) number with situational constraints (Dvorak 1984). A current intensity (CI) number is determined considering the T number and TC stages (Lushine 1977). The tables in K90 convert the CI number to MSLP and Vmax. The K90 tables were constructed with the match-up of satellite imagery and JMA best track[2] datasets from 1981 to 1986, when aircraft observation missions flown by

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[1] K90 was written in Japanese, but the main content was translated into an English version, Koba, H., T. Hagiwara, S. Osano, and S. Akashi, 1991a: Relationships between CI Number and minimum sea level pressure/maximum wind speed of tropical cyclones. *Geophysical Magazine*, **44,** 15-25.

[2] Note that RSMC Tokyo was established in 1989 after the study period of 1981–1986. While the archived best track data is currently managed by RSMC Tokyo, we use the term JMA best track, which is typically referred to as the RSMC Tokyo best track.

the U.S. Air Force in support of the Joint Typhoon Warning Center (JTWC) were routinely conducted.

The sample mean of the estimated TC intensity in each CI number category based on K90 was shown to be reasonable (Kitabatake et al. 2018; Knaff and Zehr 2007). However, the individual TC intensities contained errors in some cases. For example, Ito et al. (2018) reported that the difference in the MSLP was -10 hPa (935 and 925 hPa) at 06 UTC on October 21, 2017, and +15 hPa at 00 UTC on October 22 (915 and 930 hPa) for TC Lan (2017) between the K90-based estimations and aircraft dropsonde observations in Tropical cyclones-Pacific Asian Research Campaign for Improvement of Intensity estimations/forecasts (T-PARCII), which penetrated the eyewall of the intense TC with a Gulfstream II jet. The data assimilation of T-PARCII dropsonde observations in Ito et al. (2018) showed that the intensity forecast errors generally decreased when the real-time analysis was used as a baseline; however, they increased when the best track was used. In that case, the dropsonde-based estimate of the MSLP was closer to the real-time analysis, suggesting that the intensity forecast skill could not be correctly evaluated owing to the uncertainties in the intensity estimation. In fact, the estimated root mean squared difference (RMSD) of the individual MSLP data from the regression line in K90 is similar to the 24-h forecast errors, as shown in Section 2. Accurate TC intensity analysis is also important for forecasts because it is used as bogus observations in data assimilation and inputs for wave and storm surge forecasts. Furthermore, improved quality contributes to the evaluation of the impacts of climate change on TCs (Kawabata et al. 2023).

The errors in individual TC intensity analyses partly stem from the difficulty in specifying CI numbers (Bai et al. 2023; Bai et al. 2019; Nakazawa and Hoshino 2009). Although the difference in the estimated CI numbers among operational centers is generally small (Bai et al. 2023), the value is sometimes dubious, for example, because upper-level clouds mask the structure (Yamada et al. 2021). In addition to the specification of the CI number, the residual from the regression line in K90 imposes errors in individual TC intensity estimations, even with the correct CI number. When the K90 table was constructed, an individual MSLP observed by aircraft from 1981 to 1986 often deviated significantly from the regression curve, as shown in Fig. 1. The final TC intensity estimate is assigned based on the CI number in the current K90 procedure, whereas the actual TC intensity may depend on parameters other than the wrong assignment of CI numbers. The residual can be ascribed to various reasons such as measurement errors, dependency on latitude and size, differences in environmental pressure, improper treatment of observations, and incorrect specifications of CI numbers when constructing the regression. Therefore, it is necessary to determine whether there is any potential to decrease these errors.

This paper briefly reexamines the procedure of K90, and investigated the potential for improvements across four aspects: First, match-up cases should be selected carefully. For example, the K90 formula was constructed using the JMA best-track data and not necessarily aided by aircraft-based observations. Second, data processing from aircraft observations of TC intensity should be carefully checked. Third, the CI numbers can be better specified in a modern manner (Kitabatake et al. 2018). The use of reanalyzed CI numbers for TCs during 1981–1986 by Tokuno et al. (2009) reflects some updated procedures for the Dvorak technique. Finally, the explanatory variables, in addition to the CI numbers, can be considered to construct a model deriving more robust TC intensity. The last item is strongly motivated by Knaff and Zehr (2007) who developed a wind-pressure relationship by binning individual data according to latitude, TC size, storm motion, and environmental pressure, followed by a further update by Courtney and Knaff (2009). They successfully reduced the scatter of the MSLP between observations and estimations for a given Vmax. In this study, we consider the procedures outlined to develop a new model for estimating the MSLP in the western North Pacific as a function of latitude, TC size, environmental pressure, and CI number using data from 1981 to 1986.

We focused on the estimate of the MSLP rather than Vmax or the wind-pressure relationship, although we recognize that Vmax is important for disasters. This is because in the 1980s, the MSLP was reasonably measured by flight-level altitudes, which are good proxies for the MSLP, or dropsondes. In contrast, Vmax was crudely observed from on-board observations of the sea surface state and flight-level wind measurements reduced to the surface. Those Vmax observations were limited to the regions of the flight path. The final analysis of Vmax by JMA was largely due to the MSLP using an approximate form of cyclostrophic wind balance (Atkinson and Holliday 1977; Takahashi 1952). Therefore, it is reasonable to focus on the development of a reliable model for MSLP estimation in the WNP as a first step toward estimating the TC Vmax. Our perspective on Vmax estimation is provided in the concluding remarks.

The remainder of this paper is organized as follows: Section 2 briefly describes the background and methodology of the K90. In Section 3, we evaluate the selected cases, treatment of aircraft-based observations, use of reanalyzed CI numbers, and additional explanatory variables. A new model for estimating the MSLP is proposed and evaluated in Section 4, and we apply further tests in Section 5. The concluding remarks are presented in Section 6. This study aids in more accurately estimating the TC MSLP, which should lead to more reliable TC forecasts and verifications, as well as a better evaluation of the impact of climate change on TCs.

2. Revisiting K90

The objective of K90 was to compare the relationship between CI numbers and TC intensity (MSLP and Vmax) analyzed by the JMA, although the tables in Dvorak (1975) and Dvorak (1984) were available. We briefly review the processes in terms of case selection, treatment of aircraft data, CI numbers, and regression equation.

2.1 Case selection

The intensity estimates of TCs by the JMA relied on aircraft reconnaissance by the U.S. Air Force and JTWC until 1987. The JMA started to routinely derive CI numbers in March 1987 to conduct a Dvorak analysis. They used 50 TCs whose lifetime minimum for the MSLP was 950 hPa or less in the JMA best track data from 1981 to 1986, except for the seemingly incorrect specification of two TCs (TC Doyle (1984) and TC Judy (1982) as shown below). Although it is unclear why they did not employ TCs whose lifetime MSLP was higher than 950 hPa, it effectively alleviated excessive adjustment to samples for weak TCs, which degraded the intensity estimation of very strong TCs (Knaff and Zehr 2007). They used 12-hourly best track data (00 and 12 UTC) instead of the 6-hourly best track. Although 50 TCs were flown by reconnaissance aircraft at least 10 times, approximately 40% of the best track records were not aided by the aircraft observations within 3 h from the analysis time. This could be a source of uncertainty in the K90 derivations. Unfortunately, the individual records used to construct the K90 table are missing. However, we can discuss some of the basic properties of K90 using its texts, tables, and figures.

Based on the text, 50 TCs were allegedly analyzed. However, their list of TCs (Table 2 of K90) contained only 48 TCs and exhibited some inconsistencies as follows.

- TC Doyle (1984), whose lifetime minimum MSLP was 940 hPa, was not listed, although aircraft observations were available.
- The lifetime minimum of the MSLP of TC Judy (1982) in the table was 955

hPa.

- TC Dinah (1984) was misspelled as TC Dainah (1984).
- An incorrect identification number was assigned to the TCs Agnes (1981), Clara (1981), Elsie (1981), Gay (1981), Carmen (1986), Forrest (1986) and Joe (1986) in their Table 2. For example, TC Agnes was the 18th TC in 1981. This was recorded as the 20th TC in the table. The wrong identification numbers caused two TCs (Irma (1981) and Kim (1986)) to be missing in Table 2 of K90, although their lifetime MSLPs were lower than 950 hPa. This may explain why only 48 TCs are listed in this table, instead of 50. Although these two TCs are not shown in Table 2 of K90, their tracks are on the map (Fig. 1 of K90); thus, it can be assumed that they were used in the analysis of K90.

In K90, the reported total number of samples was 855. However, our count of the number of samples for the 12-hourly best track was 811 for the 50 TCs. Even when we add Doyle (1984) to the count, the number is 822. The reasons for these inconsistencies are unclear. Nevertheless, the histograms of the MSLP in the K90 record and our count for the 51 TCs were similar (Fig. 2). These factors were unlikely to affect the results and conclusions hereafter.

2.2 Treatment of aircraft data

K90 used the best track data for constructing the regression equation. The correlation coefficient between the best track MSLP and aircraft-based MSLP was as much as 0.99 when those aircraft data were available. Therefore, the best track data heavily relied on the aircraft-based observations if available. During that period, dropsondes and the converted MSLP from aircraft altitude were used. For the conversion from the aircraft altitude, the conversion formula (Watanabe's equation) was used to obtain the MSLP on those days in the JMA (Kitabatake et al. 2018).

$$P_c = 634 + 0.1194x \quad (1)$$

where x represents the aircraft altitude at 700 hPa in meters.

This study mainly focused on the MSLP estimation. However, one may be interested in the Vmax estimation. Based on an interview with a person who performed the TC intensity analysis on those days, the Vmax predominantly relied the conversion from MSLP, although the surface wind estimation and flight-level winds were frequently reported (Y. Nyomura, 2022, personal communication, October 31, 2022). We calculated the correlation coefficients between the best track Vmax and possible sources for the cases in which both the surface wind estimation and flight level winds were available. The correlation coefficient was 0.70 between the best track Vmax and surface wind estimation and 0.84 between the best track Vmax and flight level winds. In contrast, the correlation coefficient was 0.97 between best track Vmax and Vmax converted from best track MSLP, following $V_{max} = 6.0 \times \sqrt{1010 - MSLP}$ (Takahashi 1952)[3]. This strongly suggests that the best

[3] Several formulae were also used to convert from the MSLP to the Vmax on those days (Nyomura, 2022,

track Vmax depended on the best track MSLP rather than the aircraft-based information on sea surface wind estimates and flight-level winds on those days.

2.3 CI numbers

A CI number in K90 was estimated from an enhanced infrared satellite imagery according to the Dvorak technique, while a visible satellite imagery was also referenced during the daytime. Four skillful analysts have worked on this project. However, it was likely that one analyst determined the CI number, except for difficult cases in which the decision was made by two analysts. The CI number for a TC that decayed over land was determined by the algorithm in Koba et al. (1991b).

2.4 Regression equation

K90 proposed a quadratic function for the MSLP and Vmax using the CI number as the explanatory variable. The regression models derived[4] for all samples were

$$P_c = -1.53\mathrm{CI}^2 - 3.03\mathrm{CI} + 1010.01 \tag{2}$$

$$V_{\max} = 0.09\mathrm{CI}^2 + 13.49\mathrm{CI} + 8.38 \tag{3}$$

where P_c is the MSLP in hPa, and V_{max} is the 10-minute averaged wind in knot. The outputs were tabulated for operational purposes. K90 also derived models for the

personal communication, October 31, 2022).

[4] Eq. (2) is taken from Fig. 2a of K90. The equation on page 66 of K90 is incorrect.

developing and decaying cases. The MSLP was higher (lower) for CI numbers smaller (larger) than 4.0 in developing cases, while K90 recommends the use of Eq. (2) that does not consider the development rate. They mentioned an overestimation in Dvorak (1984) for the intensity of strong cyclones, which is consistent with recent surveys (Knaff and Zehr 2007).

The RMSD of the residuals between individual data and this regression equation was 12.99 hPa (including the rounding error for the best track data to 5-hPa) from Fig. 2 of K90 (Fig. 1). This implies that even if a CI number is appropriately assigned, each MSLP estimation significantly deviates from the truth. Comparing this with the root mean squared errors of recent TC intensity forecasts by JMA (11.9 and 18.1 hPa at the forecast times of 24 and 72 h from 2017 to 2021, respectively, based on RSMC Tokyo annual reports), a large error in the MSLP estimate could degrade the subsequent TC intensity forecasts through data assimilation, as well as hindering a correct evaluation of the forecast skill especially for an individual case.

3. Improvement potentials

Based on the K90 procedure reviewed, we considered the selected cases, aircraft data treatment, CI numbers, and additional explanatory variables for a better TC intensity analysis model.

3.1 Case selection

The best-track data were used to create the K90 table regardless of the aircraft observations around the specified time. If there were aircraft observations around the time of analysis, the MSLP in the best track data was expected to be more reliable. However, if there were no supportive aircraft observations around the time of analysis, the MSLP on the best track was less reliable. It is reasonable to construct a regression model using only aircraft observations from around the time of analysis including TC Doyle (1984), whose lifetime MSLP was 940 hPa. In addition, we used 6-hourly aircraft data instead of the 12-hourly data used in K90.

3.2 Treatment of aircraft data

We checked the aircraft data from 1981 to 1986, as in K90. Aircraft data from 1981 to 1985 were obtained from the JTWC annual reports while those from 1986 were provided by the JTWC. When a record was dubious, based on our basic checks, we also referred to the JMA Geophysical Review, which describes JTWC aircraft data since 1951. The basic checks were as follows.

- Some records show that the 700 hPa height was observed reportedly at the vertical level of 1,500 ft. Of course, the 700 hPa height cannot be directly observed from 1,500 ft. After checking the consistency in the succeeding aircraft reconnaissance, we assumed that this was due to a written mistake in the vertical level, which should have been 700 hPa; we used the 700 hPa height for the MSLP estimation.

- If one aircraft-based MSLP ($MSLP_a$) was spiky, the $MSLP_a$ was not used. This condition is expressed as follows:

$$|MSLP_{before} - MSLP_a| > 30 \text{ hPa},$$

$$|MSLP_{after} - MSLP_a| > 30 \text{ hPa},$$

$$(MSLP_{before} - MSLP_a)(MSLP_{after} - MSLP_a) < 0,$$

where $MSLP_{before}$ and $MSLP_{after}$ are respectively the aircraft-based MSLPs obtained within 6 h before and after the observation time of $MSLP_a$.

- If the 700 hPa height was greater than 3,200 m, the data were not used.
- When both dropsondes and flight altitudes were available for MSLP estimation, the data were not used if the two estimates deviated by more than 10 hPa.

To convert an aircraft altitude to an MSLP, we employed the following formula from Jordan (1958):

$$P_c = 645 + 0.0115x \tag{4}$$

We used this formula from Jordan (1958) instead of Eq. (1) because Watanabe's formula incurs an estimation bias. A comparison between the dropsonde-derived MSLP and the MSLP converted from aircraft altitude using Eq. (1) shows that the altitude-derived MSLP tended to have negative bias for very strong TCs while it tended to have positive bias for moderate-to-weak TCs (Fig. 3a). Thus, the MSLP estimated from the flight altitudes according to Eq. (1) may have caused a bias. The optimal linear regression between the altitude and dropsonde data was as follows:

$$P_c = 646 + 0.01145x \quad (5)$$

This is significantly closer to the relationships in Eq. (4) as in Jordan (1958); therefore, the use of Jordan's formula enhances the consistency between dropsonde-derived MSLPs and MSLPs converted from altitude. Dropsondes provide direct observation of the MSLP and serve as a reference. They were used in our new TC intensity analytical model. whereas we admit that the dropsonde-derived MSLP sometimes deviates from the true MSLP by a few hPa. For example, it is difficult to accurately detect the center of a weak TC without a clear eye. In addition, the location of an observation can be slightly away from the surface center horizontally and vertically. The National Hurricane Center corrects the MSLP according to the observed splash wind. However, we are unsure that this type of correction was not applied on those days. The actual splash wind was at least not accurately observed at that time.

3.3 CI numbers

Although the original CI number records used by K90 are missing, the reanalyzed CI numbers of Tokuno et al. (2009) were available for TCs from 1981 to 1986. This version treats CI numbers as follows:

- The largest T number in the lifetime of the TC was determined first. Subsequently, a Dvorak analysis was conducted forward and backward in time, which worked better for estimating the intensity of a rapidly evolving TC. We note that this is not in the JMA operational real-time analysis procedure.
- The 6-hourly analysis was conducted with 3-hourly animated images.
- The square-lattice projection was used. This projection is less affected by image distortion.

Kitabatake et al. (2018) stated that the quality of the CI numbers is presumably better in terms of the accuracy and homogeneity.

3.4 Additional explanatory variables

Knaff and Zehr (2007) explained that the TC tangential wind speed, v, and the TC MSLP, P_c, are related through the gradient wind balance as follows:

$$P_c = -\int_0^R \rho \left(\frac{v^2}{r} + fv \right) dr + P_{env} \qquad (6)$$

where ρ is the density, r is the distance from the center, R is the radius of interest, f is the Coriolis parameter, and P_{env} is the environmental pressure. This equation states that the MSLP is not solely a function of tangential wind and thus supports the idea of using the TC size, Coriolis parameter (or latitude), and environmental pressure for the pressure-wind relationship (Bai et al. 2023; Courtney and Knaff 2009; Knaff and Zehr 2007). Under the framework of K90, which considers the relationship between the MSLP and CI number (not the relationship between the MSLP and Vmax), it is worth investigating how the MSLP is related to parameters other than the CI numbers. The CI number is determined by the cloud status around the TC center and reflects its vorticity, convection, core temperature, and the effect of environmental vertical wind shear (Velden et al. 2006). It relies less on TC size, latitude, and environmental pressure. Therefore, it is reasonable to include the size, latitude, and environmental pressure as explanatory variables to explain the variability in MSLPs. In addition to these variables, K90 showed that the relationship between the MSLP and CI numbers also depended on the development rate of a TC. It may be valuable to include the development rate as an additional explanatory variable.

Our regression model is similar to those developed by Knaff and Zehr (2007) and others with several differences. Previous models have considered the translation speed of a TC. However, we did not consider the TC translation speed to adjust the wind speed because the regression model in our study did not explicitly consider the wind. We also propose a model in which the product of latitude and TC size is treated as an explanatory variable, in addition to one that considers latitude and TC size as two independent variables. This is because Eq. (6) indicates that the product is more relevant to the MSLP.

4. MSLP model

4.1 Regression equations and data treatment

Based on these considerations, we tested nine equations, as summarized in Table 1. The original equation proposed by K90 is referred to as CTRL. The other equations employ Jordan's conversion formula from aircraft altitude to MSLP, while CTRL employs Watanabe's formula. The JORDAN experiment was performed to show the dependence of the skill to the different conversion formulae. The CIOPTIM equation is the quadratic regression expression optimized for the CI numbers in Tokuno et al. (2009). DEVELOP, LAT, SIZE, and PENV are similar to CIOPTIM but they each add the development rate, latitude, size, and environmental pressure as an explanatory variable in the regression expressions. The TEST1 equation considers the CI number, development rate, latitude, size, and environmental pressure as explanatory variables. The TEST2 equation is similar to the TEST1 equation, but employs the product of latitude and size as one explanatory variable instead of independently employing latitude and size as two explanatory variables. Through this series of equations, we aimed to clarify the improvement of the MSLP estimation using updated CI numbers, updated altitude-MSLP relationships, and additional explanatory variables discussed in Section 3.4 on the MSLP estimation against the calibrated aircraft-based MSLP observations (dropsonde or flight-level altitude).

We used 6-hourly aircraft-based MSLP observations for 51 TCs whose lifetime MSLP was 950 hPa or lower from 1981 to 1986 except for TC Judy (1982). The sampled TCs were presumably the same as in K90, except TC Doyle (1984) was added in the current analysis.

We employed CI numbers from Tokuno et al. (2009). In the operational procedure of the JMA, the maximum change in T numbers should be equal to or smaller than ±1.0 in 6 h, ±1.5 in 12 h, ±2.0 in 18 h, and ±2.5 in 24 h (Kitabatake et al. 2018). Tokuno et al. (2009) constructed two versions of CI numbers with and without the limitation. We show the results without this limitation because the RMSD was slightly smaller (approximately 0.4 hPa in TEST1). After applying the basic quality controls mentioned in Section 3.2, the 6-hourly MSLP was calculated from dropsondes or flight-level altitudes only when aircraft data were available within 3 h of the analysis time. When both dropsonde- and altitude-based MSLPs were available (444 cases), their mean was employed as the observed MSLP because the errors in dropsonde- and altitude-based MSLPs likely cancel out[5]. When multiple aircraft missions were conducted within 3 h of the analysis time, only one mission nearest to the analysis time was used. If the TC center was located within 0.1° from the land in the last 12 h, the data were not used. We tested Eqs. (1) and (4) for the conversion of aircraft altitude to the MSLP. In total, 877 records were used to construct the regression models.

Latitude, used as the explanatory variable, was obtained from the JMA best track. The change in the CI number (δCI_{24}) is represented by the difference between the current

[5] The RMSD of TEST1 in Table 1 was 9.60 hPa by employing a dropsonde observation for the MSLP for these 444 cases while the corresponding RMSD was 9.55 hPa by employing the average of a dropsonde observation and altitude-inferred estimate with the same samples.

CI number and the CI number 24 h prior. If the CI number 24 h prior was not available, the change in the CI number was set to zero. The radius of the 30-kt wind (R30) in the JMA best track from 1981 to 1986 was available and appears to fit the operational purpose. The official R30 was basically determined based on reports from ships and buoys, satellite observations, and clouds from those days but MSLP might bereferred (JMA 1990). Thus, the use of the best track R30 as an explanatory variable is not appropriate to derive a regression equation. Another potential issue is that the characteristics of the official R30 estimates have substantially changed over the last several decades. The correlation coefficient between R30 and MSLP was -0.61 from 1981 to 1986, while it was -0.40 from 2016 to 2021. This implies that an optimized model with R30 on those days does not show the envisaged skill in operational use to date. Therefore, we employed a radius for the azimuthal-mean tangential velocity of 20 kt in ERA5 (Hersbach et al. 2020) for the TC size ($R20_{ERA}$) because the size of a TC in ERA5 is not directly affected by the MSLP. We determined the TC center in ERA5 as the location of the MSLP minimum after applying the smoothing of 3x3 grids and calculated the azimuthal-mean tangential velocity about the TC center. When the maximum azimuthal-mean tangential velocity in ERA5 was less than 20 kt or the TC size was smaller than 100 km, the TC size was set to 100 km. Environmental pressure was calculated as the average within the ring between $R20_{ERA}$+100 km and $R20_{ERA}$+300 km. In Section 5.2, we show the results of additional experiments that employed the R30 in the JMA best track, Japanese 55-year Reanalysis (JRA55;

Kobayashi et al. 2015), or the radius of the outermost closed isobar (ROCI).

4.2 Results

The coefficients of each regression model are summarized in Table 2, and their RMSDs with respect to the aircraft data are shown in Table 3 and Fig. 4. Table 3 lists two RMSDs to quantify the adverse effect of the rounding of aircraft-based MSLPs and regression model outputs to 5-hPa on the intensity estimation. The rounding to the nearest 5-hPa was applied to be fair with the RMSD of the MSLP from Fig. 2 in K90 (12.99 hPa). The RMSD of CTRL was 12.54 hPa without rounding to the 5-hPa bin. This is smaller than the estimated RMSD of K90, as discussed in Section 2. The differences arise from the different case selections and CI numbers, as well as the rounding. Out of these factors, the rounding to the 5-hPa bin explains the increase of 0.08 hPa (Table 3). Assuming that the CI numbers in Tokuno et al. (2009) are closer to the current JMA operational Dvorak analysis than K90, the operational Dvorak analysis with the K90 table does not degrade the quality of the TC intensity. JORDAN yields an RMSD of 12.29 hPa, which is smaller than those in CTRL. This is due to the better consistency between the dropsonde-based MSLP and MSLP converted from aircraft altitude using Jordan (1958). CIOPTIM yields an RMSD of 11.86 hPa, which is lower than those of CTRL and JORDAN. This presumably reflects the smaller scatter from the better specification of the CI numbers in Tokuno et al. (2009).

By adding either the development rate, latitude, TC size, or environmental pressure as an explanatory variable (DEVELOP, LAT, SIZE, PENV), the RMSDs decreased by 0.48–1.40 hPa relative to CIOPTIM. This suggests that the addition of these parameters to the CI numbers partly explains the scatter of the MSLP, as in the addition of these parameters to Vmax in Knaff and Zehr (2007). In particular, a significant improvement was achieved when the latitude or size was added as an explanatory variable.

TEST1 considered all additional four parameters as explanatory variables, with size and latitude as independent variables. The RMSD of TEST1 was 9.34 hPa, which was 25.5% lower than that of CTRL. This suggests that the optimization with CI numbers through modern methods and the consideration of additional parameters can substantially improve the quality of the estimated MSLP for a better match to aircraft-based observations that use the well-calibrated altitude-MSLP relationship.

The coefficients for size and latitude had negative signs in the regression equation of TEST1 (Table 2), indicating that a lower MSLP was calculated for a large TC at higher latitudes for a given CI number. This is reasonable because the CI number is relevant to the structure around the TC center. The impact of size and latitude on the MSLP in Eq. (6) persists over a broad area of the environment. The development rate term had a positive sign. This implies that the weakening (intensifying) TC should be stronger (weaker) for a given CI number. Thus, the change in the actual TC intensity lags behind the CI-number change.

Fig. 5 shows the relationship between the aircraft-derived MSLP and the modeled MSLP in CTRL and TEST1. A better fit was evident for all categories in the TEST1 model. Cases with large analysis errors substantially decreased in TEST1 (Table 3 and Fig. 5). The number of cases with a deviation of more than 25 hPa was 43 in CTRL, while it was only 7 cases in TEST1. The regression model of TEST1 was stable because the busted estimate was much less likely to occur. It is also notable that no models reasonably reproduce the intensity of a TC with an MSLP < 900 hPa. This is an issue in intensity analysis to be solved. One potential issue might be a specification of cloud patterns for a CI number of 8.0. The CI number in K90 and Tokuno et al. (2009) was 7.5 at most; the Dvorak-based TC MSLP could not be substantially lower than 900 hPa. Although the number of the relevant samples is not large, this issue should be revisited in the future.

The large error cases in TEST1 include three samples from TC Forrest (1983). For example, the recorded T and CI numbers for TC Forrest (1983) were 5.5 and 6.0, respectively, yielding 936 hPa in TEST1 at 12 UTC on September 23, 1983 while the dropsonde observation indicated 902 hPa. This is possibly because of the low resolution of the satellite that was unable to capture a small TC eye. Aircraft reconnaissance reported a small circular eye with a diameter of 6 miles. In contrast, Tokuno et al. (2009) reported a ragged eye, which indicates a ragged eyewall or an indistinct eye, for this CI number from a satellite image captured at that time. If the satellite images were of high resolution, as in current satellites, the CI number would be higher. In another case of TC Kit (1981) at 00 UTC on December 19, the aircraft-based intensity was 975 hPa, which was significantly weaker than the output of TEST1 (946 hPa). The CI number analyzed by Tokuno et al. (2009) was 6.0 for this case, while the CI number analyzed by JTWC was 4.5. In this case, the difficulty for CI number specification possibly affects the error.

TEST2 is the same as TEST1, except that the product of the size and latitude is used as an explanatory variable instead of employing them independently as two explanatory variables. The RMSD of TEST2 (9.32 hPa) is very similar to that of TEST1 (9.34 hPa). There is a strong correlation between the TC size and latitude, as TC circulations generally expand as they move poleward. This could be a reason why the results did not differ significantly.

5. Discussion

5.1 Cross validation

One may wonder whether the TEST1 and TEST2 models exhibits better skills simply because they are explained by several parameters. To ensure the integrity of the TEST1 and TEST2 models, K-fold cross-validation was applied. In the K-fold cross-validation, one-year data from 1981 to 1986 were used for validation, whereas data from the other five years were used to construct the regression equation. Table 4 presents the RMSDs values. The TEST1 model exhibited 22.7% better skill compared with the CTRL model. The TEST2 model performed slightly better than the TEST1 model. This is presumably because the smaller number of explanatory variables in TEST2 can explain the variability as much as TEST1.

5.2 Dependency on the definitions of size and environmental pressure

Here we tested the dependence of model performance on the choice of a TC size and environmental pressure. As for the size, we tested a radius of the azimuthal-mean tangential velocity of 20 kt (R20) and a radius of the outermost closed isobar (ROCI) in JRA55 and ERA5 as well as R30 in the JMA best track. In the calculation of R20 and ROCI, we first applied the smoothing by taking the average of 3 × 3 grids to suppress grid-scale noises. A TC center was defined as the location exhibiting the MSLP in the smoothed field. The procedure to calculate the ROCI and relevant environmental pressure is as follows: (1) grid points are defined at 1 km radially and 0.5° azimuthally within 2000 km from the TC center. (2) An innermost radius is calculated for a given sea level pressure (initially an MSLP rounded up to the next integer) in each radial leg from the center to 2000 km. (3) An isobar is regarded as closed if the differences in two detected radii between neighboring radial legs are all smaller than the corresponding azimuthal distance. (4) When an isobar is closed, we add 1 hPa for a sea level pressure of interest and resume the process (2). If the isobar is not closed, the mean radius of the outermost closed isobar is regarded as the ROCI. (5) Finally, the environmental pressure was defined as the sea level pressure at ROCI plus 1 hPa. When R20 or ROCI was smaller than 100 km, the TC size was set to 100 km. R30 in the JMA best track is the simple mean of the longest and shortest radius of 30 kt winds. The set of experiments are summarized in Table 5.

Table 6 lists the derived equations and RMSDs for LAT, PENV, TEST1, and TEST2. Generally, the difference in performance was not sensitive to the choice of the reanalysis dataset; the RMSDs for R30 in the best track were similar to those with R20 based on the reanalysis. The comparison between experiments C, D, E, and F indicates that the skill was not much sensitive to the ring radius for environmental pressure when R30 in the best track is employed. Dataset A exhibited the good skill while ERA5 does not take account for the MSLP through TC bogussing. The use of ROCI for the size and environmental pressure slightly degraded the skill, except for PENV.

6. Summary and concluding remarks

The conversion table in Koba et al. (1990) from a CI number to a TC intensity measure (Vmax or MSLP) has been used by the JMA. Recent research has shown that the overall quality of this table is acceptable as a mean value, and it has made the gigantic contribution to operational analyses and forecasts. However, the RMSD of the individual MSLP records with respect to the regression line was estimated to be as much as 13.0 hPa. Deriving a better model for improved intensity estimates is therefore desirable, leading to better forecasts and verifications. To do so, we revisited the procedure in Koba et al. (1990) and investigated the potential for improvements through case selection, aircraft data checks, the use of reanalyzed CI numbers, and adding explanatory parameters.

First, the case selection process was re-examined. The reference data were originally obtained from the 12-hourly JMA best track for a TC whose lifetime minimum MSLP was 950 hPa or less based on Koba et al. (1990). In this study, 6-hourly reference data were taken from the aircraft-based MSLP within 3 h of the TC intensity analysis only when aircraft-based observations were available. We noticed that the conversion formula from aircraft altitude to MSLP used in the JMA at that time caused biases. Correction of the conversion formula decreased the RMSDs. We used the CI numbers in Tokuno et al. (2009) obtained through a modern procedure. Re-optimization of the coefficients in the formula further decreased the RMSDs. In addition to these treatments, we considered additional explanatory variables (development rate, size, latitude, and environmental pressure) in the MSLP estimation model. We found that all of them contributed to decreasing the RMSDs, of which size and latitude were important.

When we consider all of these factors, the derived models achieved the RMSDs as small as 9.34 and 9.32 hPa in the model construction and 9.69 and 9.54 hPa K-fold cross validation in the following models (TEST1 and TEST2 in Table 2), respectively.

$$P_c = -2.17\mathrm{CI}^2 + 5.43\mathrm{CI} + 1.73\delta\mathrm{CI}_{24} - 0.367\Phi - 0.0227R - 5.78 + P_{\mathrm{env}} \qquad (7)$$

or

$$P_c = -2.21\mathrm{CI}^2 + 5.68\mathrm{CI} + 1.39\delta\mathrm{CI}_{24} - 0.00113\Phi R - 12.81 + P_{\mathrm{env}}. \quad (8)$$

Compared to the CTRL, the residual with respect to aircraft observations decreased by more than 25% in the model construction (Table 3) and 22% in the verification (Table 4). If we compare with the original table in Koba et al. (1990) that had approximately the RMSD of 13.0 hPa (Fig. 1), the RMSD reduced by more than 28% to 9.3 hPa in the optimization. Based on these coefficients, a large TC at high latitudes with low environmental pressure tended to have a low MSLP in the model for a given CI number. This also suggests that the change in the actual TC intensity lagged the change in the CI number. Additional information on the size and latitude may decrease the scatter of the MSLP data. This may reflect that the CI number is relevant to the structure around the TC center, while the MSLP is also dependent on the outer environment. We also showed that the results are robust but there is some dependency on the definition of the size, environmental pressure, and the dataset (Table 6). The new regression models can contribute directly to intensity estimation, indirectly to forecasting, verifying forecasts, and monitoring the impacts of climate change.

Note that the general relationship between the CI number and MSLP has possibly changed over the last 40 years. This question should be revisited by further aircraft missions in the WNP and by considering the physical understanding of CI numbers in the future. Also, the full use of microwave images and automation contribute to further improving the quality of CI numbers (Olander and Velden 2019; Oyama 2014). This is another important topic for investigation.

In this study, we did not extensively discuss the Vmax estimation. Many studies and operational centers consider the procedure in which a forecaster first estimates Vmax and proceeds to the conversion to the MSLP through the wind-pressure relationship. The Vmax in the best track data was predominantly due to conversion from the MSLP in the WNP because of the difficulty in Vmax observations from 1981 to 1986 (see also supplemental material). If we estimate the MSLP by converting the Vmax to the MSLP, it suffers from the combined effect of the Vmax estimation and conversion errors. It is scientifically sound to first develop a model for the MSLP as accurately as possible and then derive Vmax because the MSLP reference is relatively reliable. The uncertainty of the MSLP can be quantified as in this study. The development of a procedure to derive Vmax is highly important for disaster prevention and mitigation. For this purpose, one possible means is to convert the MSLP to the Vmax through the wind-pressure relationship based on Knaff and Zehr (2007), which is relatively reliable with in situ and remotely sensed observations in the Atlantic and eastern Pacific regions. Another possible method is to synthesize various observations such as dense dropsonde observations near the TC inner-core region (Yamada et al. 2021), ground-based Doppler radar (Shimada et al. 2016), and synthetic aperture radar (Zhang et al. 2014) in the WNP, which is beyond the scope of this study.

Supplement

The supplement shows the skill of regression models using the MSLP and Vmax in the best track data as a reference value.

Data Availability Statement

The TC best-track data are available online on the RSMC Tokyo website (https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/trackarchives.html). Dvorak reanalysis data were provided from RSMC Tokyo upon request. Aircraft observation data from 1981 to 1985 were obtained from JTWC annual reports (https://www.metoc.navy.mil/jtwc/jtwc.html?cyclone); data for 1986 were provided from JTWC upon request. Aircraft observation data during the study period are also available in the Geophysical Review (No. 967 to No. 1036), which was published monthly by the JMA. ERA5 data were downloaded from the Copernicus website (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview).

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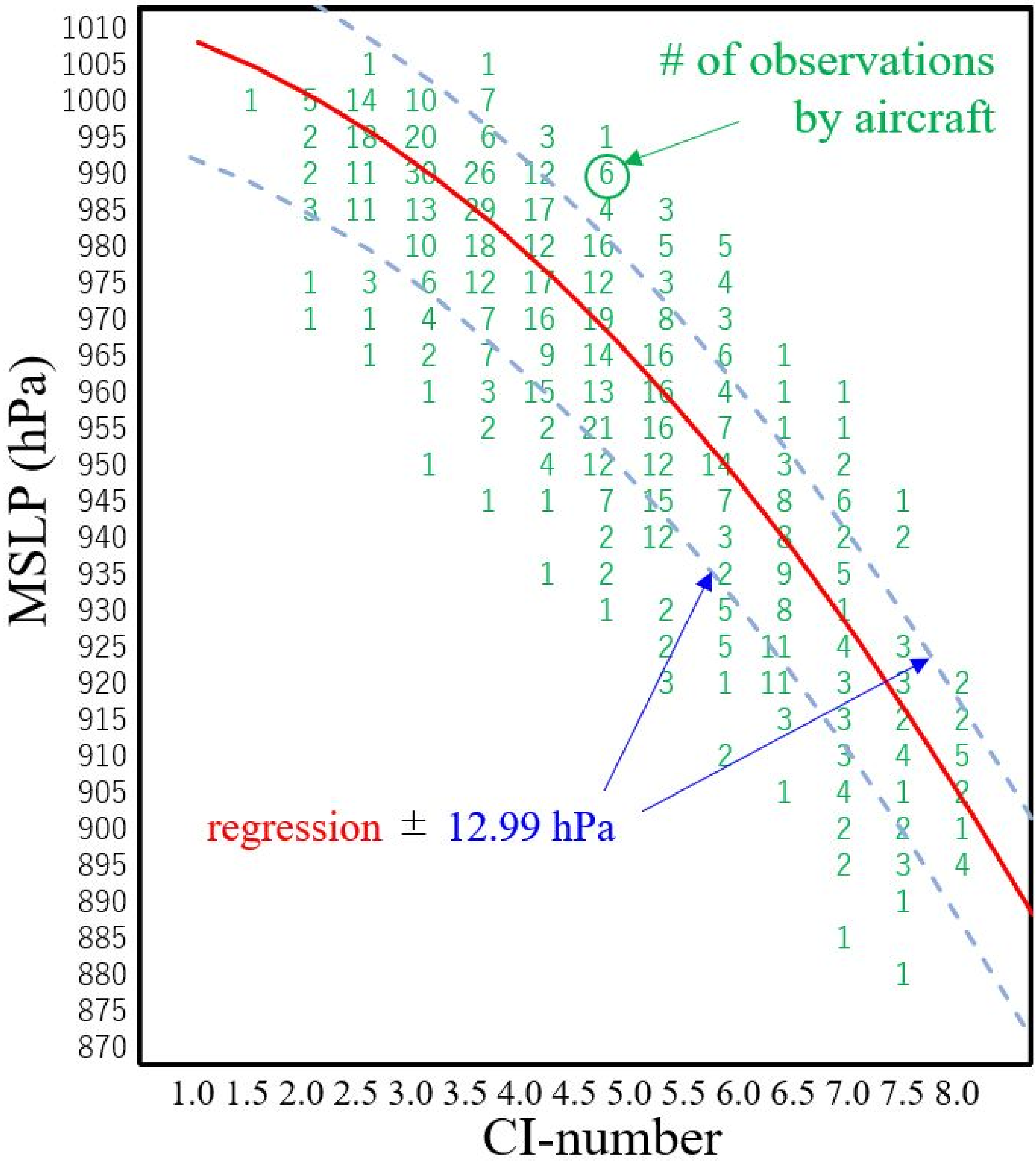

Fig. 1. Number of samples used to construct a regression curve connecting the CI numbers to the MSLP (reproduced from the numbers in Fig. 2a om K90). A standard deviation of 12.99 hPa from the regression curve is also shown.

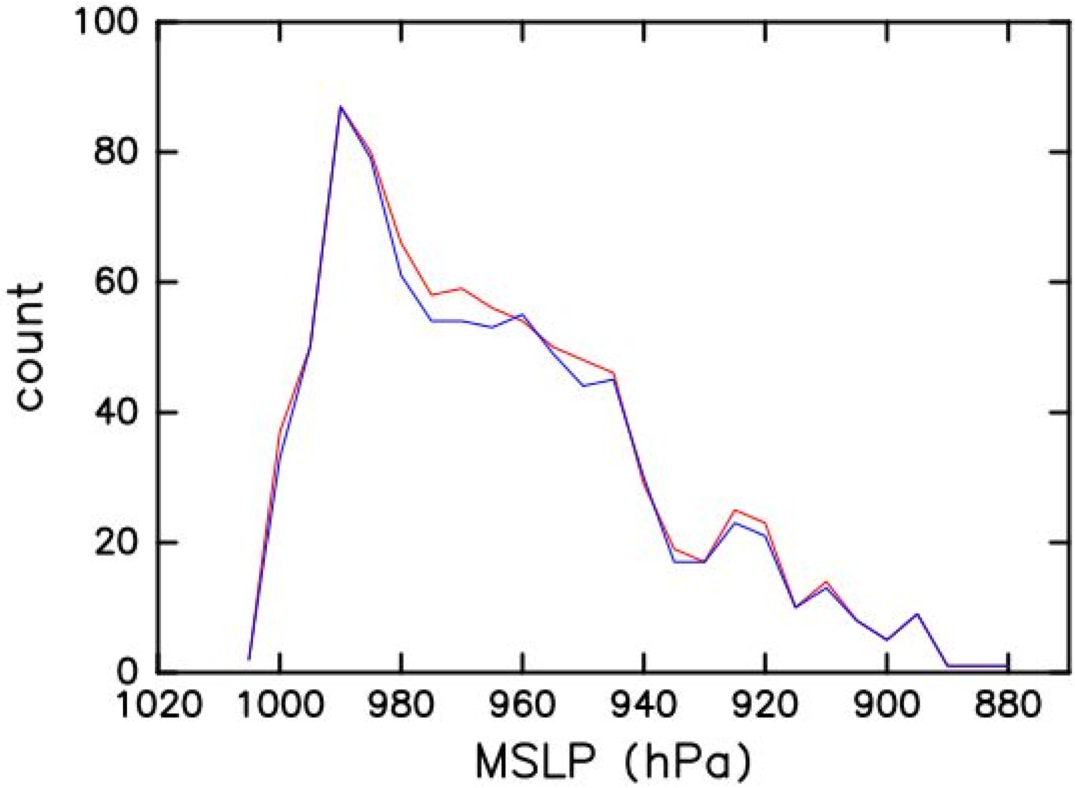

Fig. 2. Number of samples from Fig. 2 in K90 (red) and our count for the 12-hourly best track data (blue).

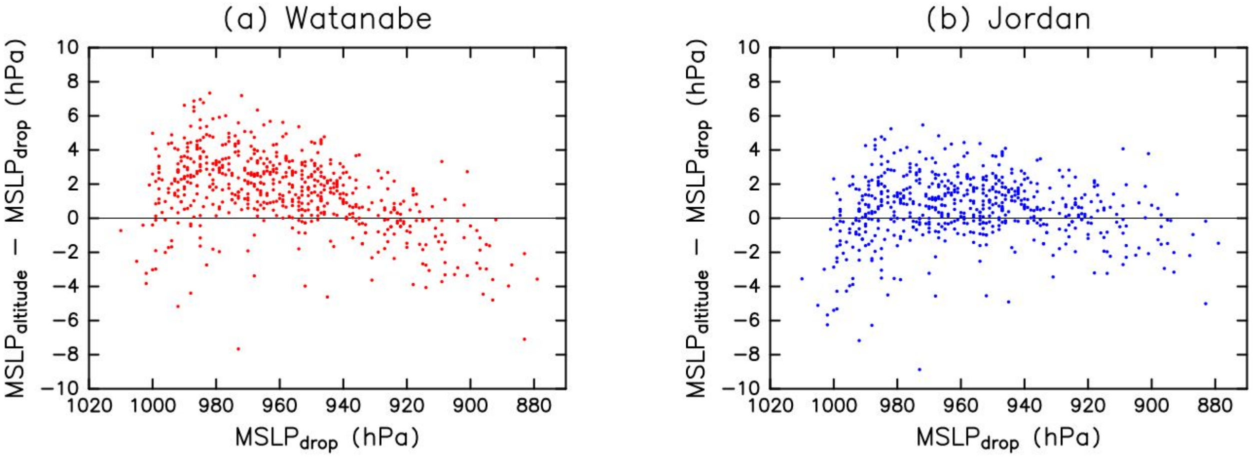

Fig. 3. Anomaly in the converted MSLP from aircraft altitude with respect to the dropsonde-based MSLP. The conversion uses (a) Watanabe's equation and (b) Jordan's equation.

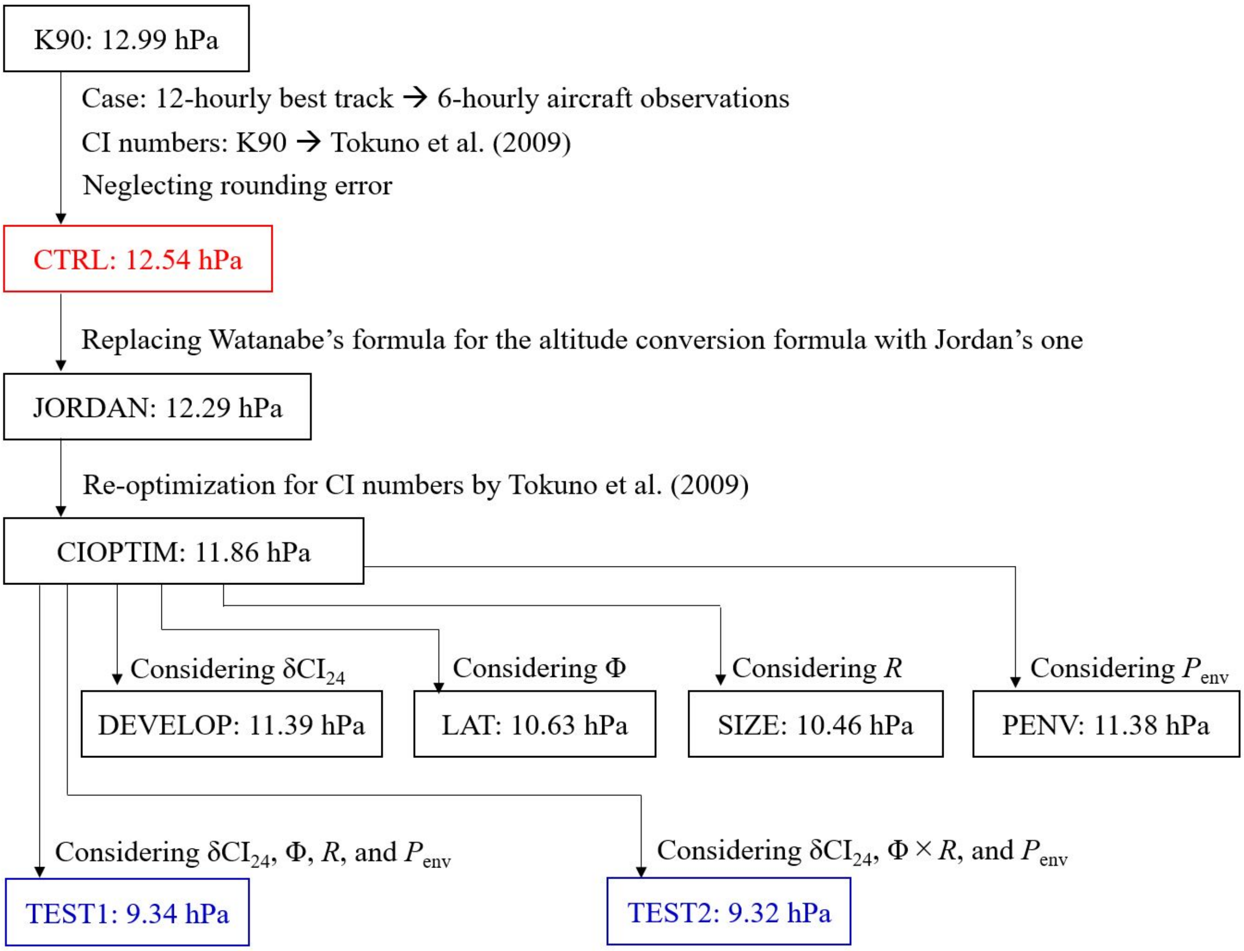

Fig. 4. Relationship between the regression models and their RMSDs.

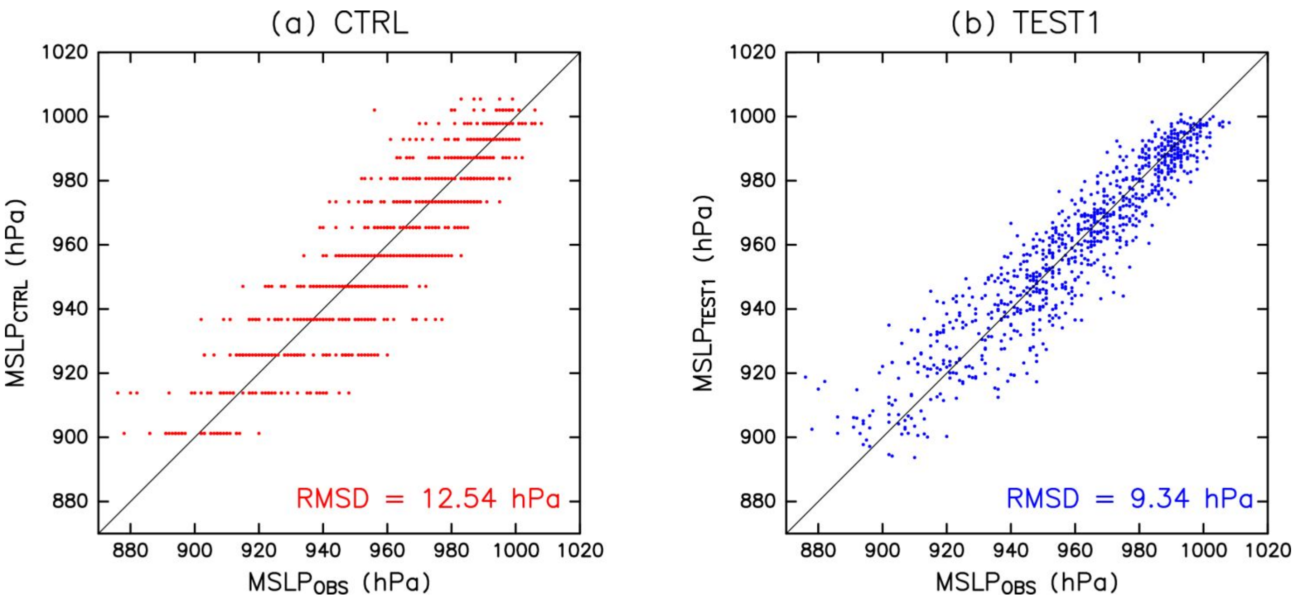

Fig. 5. Comparison of aircraft-based observations and regression models for CTRL and TEST1.

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Table 6. Derived equations and RMSDs of LAT, PENV, TEST1, and TEST2 for the experimental set in Table 5.

Table 1. Regression models tested in this study. Φ is latitude in degrees and R is a size parameter in km.

name	equation for P_c	altitude-MSLP conversion
CTRL	$-1.53\mathrm{CI}^2 - 3.03\mathrm{CI}+1010.01$	Watanabe
JORDAN	$-1.53\mathrm{CI}^2 - 3.03\mathrm{CI}+1010.01$	Jordan
CIOPTIM	$a_1\mathrm{CI}^2 + a_2\mathrm{CI}+a_3$	Jordan
DEVELOP	$a_1\mathrm{CI}^2 + a_2\mathrm{CI}+a_3\delta\mathrm{CI}_{24} + a_4$	Jordan
LAT	$a_1\mathrm{CI}^2 + a_2\mathrm{CI}+a_3\Phi + a_4$	Jordan
SIZE	$a_1\mathrm{CI}^2 + a_2\mathrm{CI}+a_3R + a_4$	Jordan
PENV	$a_1\mathrm{CI}^2 + a_2\mathrm{CI}+a_3 + P_{\mathrm{env}}$	Jordan
TEST1	$a_1\mathrm{CI}^2 + a_2\mathrm{CI}+a_3\delta\mathrm{CI}_{24} + a_4\Phi + a_5R + a_6 + P_{\mathrm{env}}$	Jordan
TEST2	$a_1\mathrm{CI}^2 + a_2\mathrm{CI}+a_3\delta\mathrm{CI}_{24} + a_4\Phi R + a_5 + P_{\mathrm{env}}$	Jordan

Table 2. Coefficients in the regression models.

name	equation for P_c
CIOPTIM	$-1.95\mathrm{CI}^2 + 2.64\mathrm{CI} + 994.12$
DEVELOP	$-1.98\mathrm{CI}^2 + 2.21\mathrm{CI} + 2.88\delta\mathrm{CI}_{24} + 995.91$
LAT	$-2.31\mathrm{CI}^2 + 6.41\mathrm{CI} - 0.911\Phi + 1001.66$
SIZE	$-1.97\mathrm{CI}^2 + 4.09\mathrm{CI} - 0.0282R + 999.39$
PENV	$-2.00\mathrm{CI}^2 + 3.01\mathrm{CI} - 14.13 + P_{\mathrm{env}}$
TEST1	$-2.17\mathrm{CI}^2 + 5.43\mathrm{CI} + 1.73\delta\mathrm{CI}_{24} - 0.367\Phi - 0.0227R - 5.78 + P_{\mathrm{env}}$
TEST2	$-2.21\mathrm{CI}^2 + 5.68\mathrm{CI} + 1.39\delta\mathrm{CI}_{24} - 0.00113\Phi R - 12.81 + P_{\mathrm{env}}$

Table 3. RMSD is the root mean squared differences between the model outputs and reference data that are not subjected to rounding, while <RMSD> applies rounding to the MSLPs to the 5-hPa bin. The number in the parenthesis represents the number of cases in which the deviation from the aircraft-based observation is larger than 25 hPa.

name	RMSD	$\langle$RMSD$\rangle$
CTRL	12.54 (43)	12.62 (46)
JORDAN	12.29 (44)	12.28 (39)
CIOPTIM	11.86 (36)	11.90 (31)
DEVELOP	11.39 (20)	11.45 (19)
LAT	10.63 (30)	10.69 (22)
SIZE	10.46 (20)	10.55 (19)
PENV	11.38 (29)	11.42 (32)
TEST1	9.34 (7)	9.44 (6)
TEST2	9.32 (9)	9.43 (9)

Table 4. RMSDs (in hPa) in the K-fold cross validation for CTRL, JORDAN, CIOPTIM, TEST1, and TEST2. The category "all" was calculated as the square root of the sum of squared errors in all years.

year	1981	1982	1983	1984	1985	1986	all
CTRL	12.99	11.08	15.35	12.37	10.49	12.40	12.54
JORDAN	12.75	11.03	14.79	12.10	10.20	12.22	12.29
CIOPTIM	12.10	10.65	15.26	11.95	9.26	11.35	11.99
TEST1	10.10	7.80	11.59	10.97	8.97	8.90	9.69
TEST2	9.88	7.90	11.42	10.57	8.95	8.73	9.54
samples	119	256	139	175	47	141	877

Table 5. Experiment set to check the dependency of the skill of TEST1 on the definition of size (*R*), environmental pressure (P_{env}), and dataset. The subscripts R, J, and E respectively represent the data from the JMA best track, JRA55, and ERA5. An overbar denotes an area average. Dataset A is the same as that used in Section 4.

dataset	R	P_{env}
A	$\mathrm{R20_E}$	$\overline{P_\mathrm{E}}$ $(\mathrm{R20_E}+100 < \mathrm{r} < \mathrm{R20_E}+300)$
B	$\mathrm{R20_J}$	$\overline{P_\mathrm{J}}$ $(\mathrm{R20_J}+100 < \mathrm{r} < \mathrm{R20_J}+300)$
C	$\mathrm{R30_R}$	$\overline{P_\mathrm{E}}$ $(\mathrm{R30_R}+100 < \mathrm{r} < \mathrm{R30_R}+300)$
D	$\mathrm{R30_R}$	$\overline{P_\mathrm{J}}$ $(\mathrm{R30_R}+100 < \mathrm{r} < \mathrm{R30_R}+300)$
E	$\mathrm{R30_R}$	$\overline{P_\mathrm{E}}$ $(\mathrm{R30_R}+300 < \mathrm{r} < \mathrm{R30_R}+500)$
F	$\mathrm{R30_R}$	$\overline{P_\mathrm{J}}$ $(\mathrm{R30_R}+300 < \mathrm{r} < \mathrm{R30_R}+500)$
G	$\mathrm{ROCI_E}$	P_E $(\mathrm{ROCI_E}) + 1$
H	$\mathrm{ROCI_J}$	P_J $(\mathrm{ROCI_J}) + 1$

Table 6. Derived equations and RMSDs of SIZE, PENV, TEST1, and TEST2 for the experimental set in Table 5.

name	dataset	equation for P_c	RMSD
SIZE	A	$-1.97\mathrm{CI}^2 + 4.09\mathrm{CI} - 0.0282R + 137.74$	10.46
	B	$-1.92\mathrm{CI}^2 + 3.74\mathrm{CI} - 0.0359R + 137.91$	10.35
	C, D, E, F	$-2.07\mathrm{CI}^2 + 6.17\mathrm{CI} - 0.0437R + 132.53$	10.26
	G	$-1.89\mathrm{CI}^2 + 2.69\mathrm{CI} - 0.0169R + 156.95$	11.17
	H	$-1.87\mathrm{CI}^2 + 2.45\mathrm{CI} - 0.0190R + 157.76$	11.20
PENV	A	$-2.00\mathrm{CI}^2 + 3.01\mathrm{CI} - 14.12 + P_{\mathrm{env}}$	11.38
	B	$-2.00\mathrm{CI}^2 + 3.01\mathrm{CI} - 14.43 + P_{\mathrm{env}}$	11.37
	C	$-1.98\mathrm{CI}^2 + 2.72\mathrm{CI} - 13.15 + P_{\mathrm{env}}$	11.19
	D	$-1.97\mathrm{CI}^2 + 2.57\mathrm{CI} - 12.59 + P_{\mathrm{env}}$	11.26
	E	$-1.97\mathrm{CI}^2 + 2.62\mathrm{CI} - 14.33 + P_{\mathrm{env}}$	11.36
	F	$-1.96\mathrm{CI}^2 + 2.50\mathrm{CI} - 14.04 + P_{\mathrm{env}}$	11.37
	G	$-2.06\mathrm{CI}^2 + 3.75\mathrm{CI} - 16.39 + P_{\mathrm{env}}$	11.23
	H	$-2.06\mathrm{CI}^2 + 3.68\mathrm{CI} - 16.27 + P_{\mathrm{env}}$	11.23
TEST1	A	$-2.17\mathrm{CI}^2 + 5.43\mathrm{CI} + 1.73\delta\mathrm{CI}_{24} - 0.367\Phi - 0.0227R - 5.78 + P_{\mathrm{env}}$	9.34
	B	$-2.13\mathrm{CI}^2 + 5.12\mathrm{CI} + 1.65\delta\mathrm{CI}_{24} - 0.366\Phi - 0.0279R - 1.88 + P_{\mathrm{env}}$	9.32
	C	$-2.19\mathrm{CI}^2 + 6.35\mathrm{CI} + 1.38\delta\mathrm{CI}_{24} - 0.309\Phi - 0.0317R - 6.65 + P_{\mathrm{env}}$	9.31
	D	$-2.19\mathrm{CI}^2 + 6.27\mathrm{CI} + 1.38\delta\mathrm{CI}_{24} - 0.315\Phi - 0.0323R - 5.98 + P_{\mathrm{env}}$	9.32
	E	$-2.20\mathrm{CI}^2 + 6.49\mathrm{CI} + 1.37\delta\mathrm{CI}_{24} - 0.363\Phi - 0.0320R - 7.36 + P_{\mathrm{env}}$	9.34
	F	$-2.20\mathrm{CI}^2 + 6.38\mathrm{CI} + 1.38\delta\mathrm{CI}_{24} - 0.364\Phi - 0.0320R - 7.06 + P_{\mathrm{env}}$	9.33
	G	$-2.21\mathrm{CI}^2 + 5.43\mathrm{CI} + 1.79\delta\mathrm{CI}_{24} - 0.463\Phi - 0.0153R - 3.31 + P_{\mathrm{env}}$	9.61
	H	$-2.19\mathrm{CI}^2 + 5.24\mathrm{CI} + 1.76\delta\mathrm{CI}_{24} - 0.487\Phi - 0.0173R - 0.580 + P_{\mathrm{env}}$	9.60
TEST2	A	$-2.21\mathrm{CI}^2 + 5.68\mathrm{CI} + 1.39\delta\mathrm{CI}_{24} - 0.00113\Phi R - 12.81 + P_{\mathrm{env}}$	9.32
	B	$-2.22\mathrm{CI}^2 + 5.67\mathrm{CI} + 1.27\delta\mathrm{CI}_{24} - 0.00118\Phi R - 11.46 + P_{\mathrm{env}}$	9.37
	C	$-2.23\mathrm{CI}^2 + 6.04\mathrm{CI} + 1.22\delta\mathrm{CI}_{24} - 0.00122\Phi R - 13.32 + P_{\mathrm{env}}$	9.41
	D	$-2.22\mathrm{CI}^2 + 5.94\mathrm{CI} + 1.22\delta\mathrm{CI}_{24} - 0.00124\Phi R - 12.78 + P_{\mathrm{env}}$	9.43
	E	$-2.23\mathrm{CI}^2 + 6.12\mathrm{CI} + 1.22\delta\mathrm{CI}_{24} - 0.00128\Phi R - 14.54 + P_{\mathrm{env}}$	9.43
	F	$-2.22\mathrm{CI}^2 + 6.00\mathrm{CI} + 1.24\delta\mathrm{CI}_{24} - 0.00128\Phi R - 14.25 + P_{\mathrm{env}}$	9.43
	G	$-2.23\mathrm{CI}^2 + 5.59\mathrm{CI} + 1.59\delta\mathrm{CI}_{24} - 0.000808\Phi R - 11.92 + P_{\mathrm{env}}$	9.57
	H	$-2.23\mathrm{CI}^2 + 5.59\mathrm{CI} + 1.50\delta\mathrm{CI}_{24} - 0.000845\Phi R - 11.02 + P_{\mathrm{env}}$	9.58

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