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Short-term Variation of the Vertical Field of Water Temperature Southeast off Cape Toimisaki

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Abstract

Short-term variations of the vertical temperature field, especially isothermal layer and inversion, are discussed in a section across the Kuroshio southeast off Cape Toimisaki, analysing XBT data obtained three times within a month and a half in autumn of 1979. Distinct and rather large variations have occured, due to the coastal upwelling accompanied with a coastal counter current, the intrusion of the Subtropical Mode Water towards the coast, and the intensification of the Kuroshio, which may be induced by such a weather condition as a hard northwesterly blow and so on.

1. Introduction

It is a well known fact that the path of the Kuroshio south of Japan has a bimodal distribution; one is the straight path close to the coast and the other is the large-scale meandering path far from the coast of Enshu-nada. Recent large-scale meanders of the Kuroshio have occurred in 1934–44, 1953–55, 1959–63 and 1975–80. In spite of many efforts made by various authors since the middle of the nineteen-thirties, the mechanism and the causes of the large-scale meander have not been fully clarified yet. NITANI (1975) classifies the variations of velocity and paths of the Kuroshio according to the time scale into three categories, *i.e.*, long-term (of the order of several years), medium-term (several months), and short-term (less than several weeks). SHOJI (1972), SOLOMON (1978) and others point out that a generation of a small "trigger meander" off southeast Kyushu and its subsequent eastward propagation are found before the development of large-scale meander with long-term variation. Therefore, as is suggested by SOLOMON (1978), a careful study of the "trigger meander" off southeast Kyushu seems to be a hopeful approach to the important problem of the bimodal paths of the Kuroshio.

The normal path of the Kuroshio passes always south of Yakushima Island and turns here northeastward and then proceeds off Cape Toimisaki. In order to clarify the mechanism of the "trigger meander", it must be useful to investigate the short-term variation (of the order of several weeks) of the oceanographic conditions

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southeast off Cape Toimisaki. On board the training ship Keiten-maru, Kagoshima University, the XBT (expendable bathythermograph) observations were repeated three times within a period of a month and a half in autumn of 1979 at the same section across the Kuroshio southeast off Cape Toimisaki. Another series of repeated observations with a short time interval of several weeks is rarely found in this region. Using these XBT data obtained in autumn of 1979, the short-term variations (of the order of several weeks) of the vertical temperature field across the Kuroshio southeast off Cape Toimisaki are presented in this paper as the first step to the explanation of the "trigger meander". It should be noticed that this observation period, autumn of 1979, is several months just before the disappearance of the large-scale mender in summer of 1980.

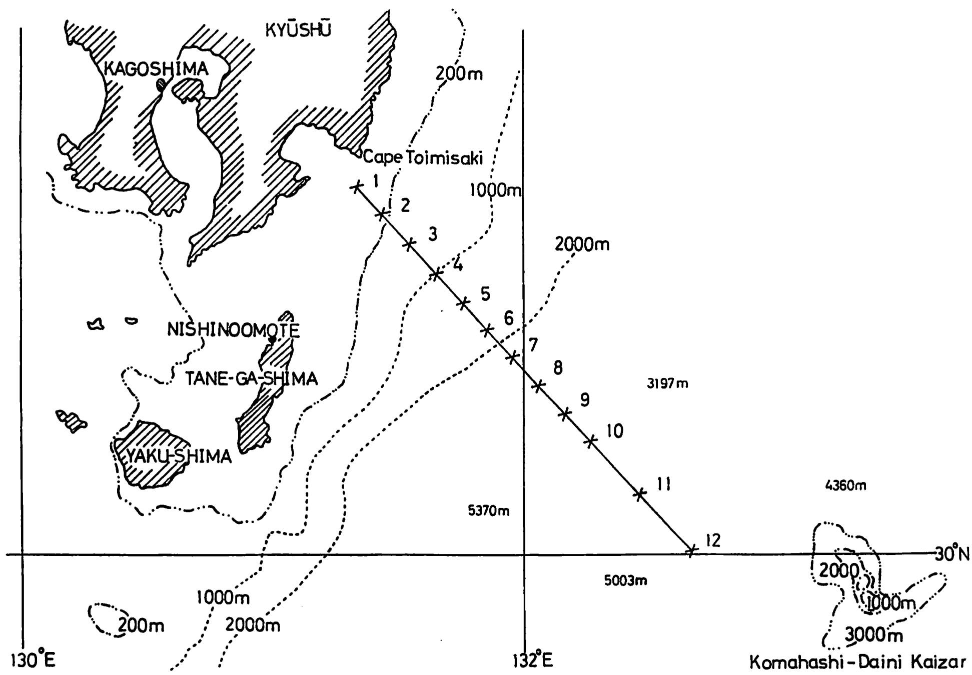


Fig. 1. Map showing the fixed positions of XBT observations.

2. Observation and the weather condition

The XBT observations are carried out on 27th October, 5th November, and 12th December in 1979, which are hereafter refered to be as Obs. I, Obs. II, and Obs. III, respectively. Fig. 1 shows the fixed positions of XBT observation. The distances between the two adjacent stations are ca 8 miles except for a few large distances of 16.5 miles. The XBT probe, casted in this observation, can obtaine the water temperature profile to a depth of ca 800 m. The XBT recorder used on board is the degital recording system of XBT data (DXBT), designed originally by the Ocean Research

Institute, University of Tokyo. Continuous signal of the output voltage from the probe is degitalized with the sampling frequency of 12 Hz and recorded on a paper tape with a ten bits binary code. This sampling frequency of 12 Hz corresponds to the depth interval of ca 0.5 m. The resolution of the temperature is less than 0.08°C depending slightly on the numerical value of actual temperature itself. Obtained data are tabulated in Appendix.

It is necessary to examine the time variation of weather condition precisely during the period of XBT observations, since the hydrographic situation in such a shallow layer as that XBT concernes will be subject to much influence of weather. The results of the meteorological observation at the Tanegashima Weather Station located in Nishino-omote city are able to utilize for this purpose. Fig. 2 shows the daily wind direction at the time when the daily maximum wind speed is observed and daily mean values of wind speed and surface air temperature at Tanegashima Weather Station during the period from 20th October to 12th December.

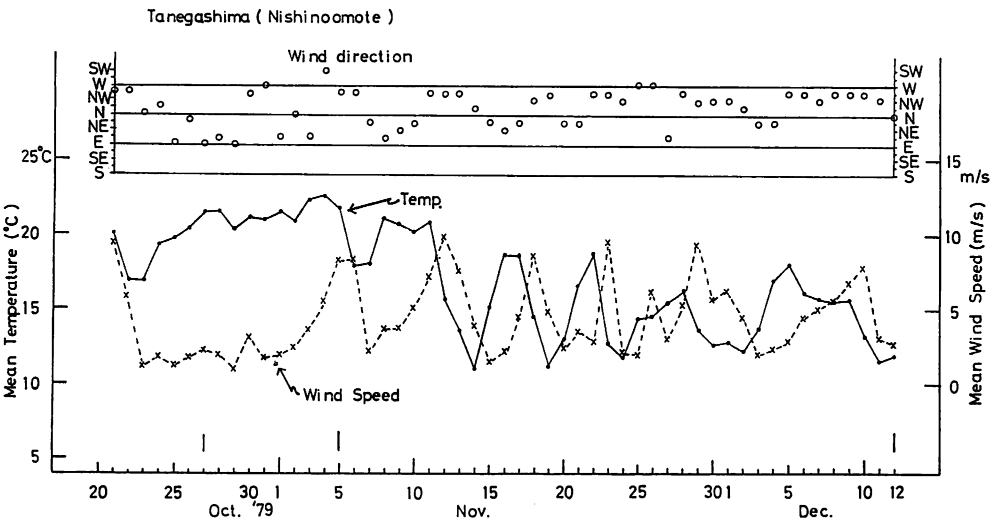


Fig. 2. Daily wind direction at the time when the daily maximum wind speed is observed and daily mean values of wind speed and surface air temperature at Tanegashima Weather Station during the period from 20th October to 12th December of 1979. Three vertical bits indicate the days of the XBT observations.

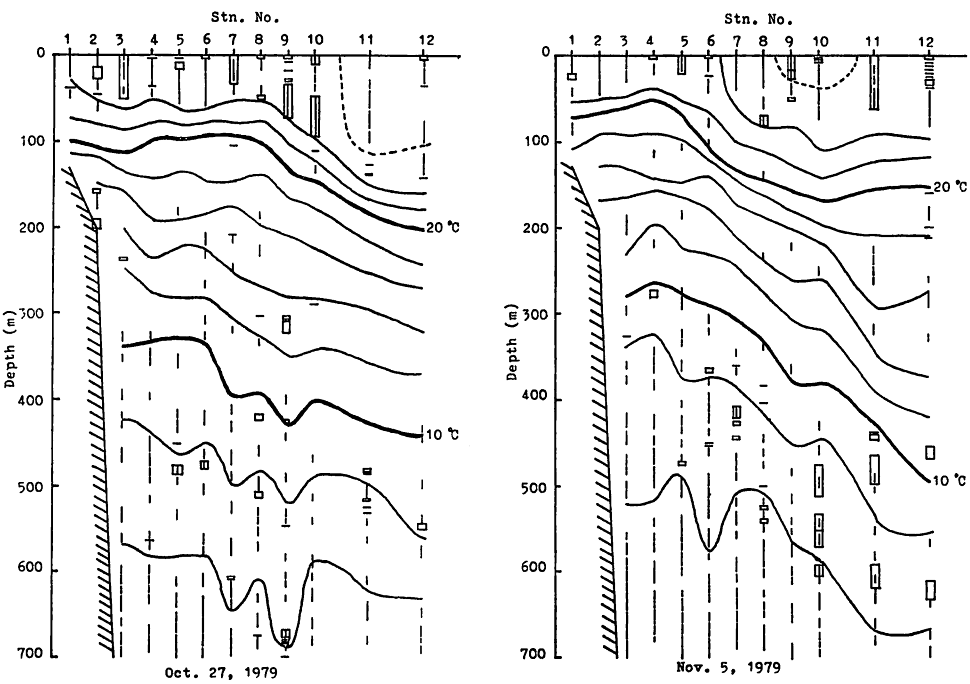
Daily mean air temperature is higher than 20°C through the period from Obs. I to Obs. II, after that it varies periodically with a period of six or seven days, maxima of ca 18°C, and minima of ca 11°C. Daily mean wind speed is less than 3 m/sec from four days before Obs. I to two days before Obs. II. Thereafter, it varies periodically with the same period as that of the mean air temperature untill Obs. III. The highest value of daily mean wind speed reaches to ca 10 m/sec on the seventh day after Obs. II. The direction of the daily maximum wind speed remains in a narrow range between NNW and WNW as far as the wind speed is rather high.

3. Short-term variations of the vartical field of water temperature

The vertical field of water temperature across the Kuroshio southeast off Cape Toimisaki obtained on Obs. I, Obs. II, and Obs. III are shown in Figs. 3a, 3b, and 3c respectively. In these figures, the open brocks and bits of horizontal solid line indicate the layers of temperature inversion and the vertical solid segments indicate the isothermal layers.

In Fig. 3a on Obs. I, the highest temperature is 25.9°C at 20 m deep of St. 12 inside the surface mixed layer above 24°C, which develops to ca 50 m deep inshore of St. 8 while it does to ca 130 m deep offshore of St. 11. Between these two stations beneath the surface mixed layer, the isotherms of 24°–20°C decline sharply southeastward.

In the subsurface layer the isotherms below 18°C decline offshore from the coast in general, which corresponds to the Kuroshio flowing toward northeast across this



(a) (b)

Fig. 3a. Vertical field of water temperature across the Kuroshio southeast off Cape Toimisaki obtained on Obs. I (27th October of 1979). The open brocks and bits of horizontal solid lines indicate the layers of temperature inversion and the vertical solid segments indicate the isothermal layers which are defined in Fig. 4.

Fig. 3b. Vertical field of water temperature across the Kuroshio southeast off Cape Toimisaki obtained on Obs. II (5th November of 1979).

section. The stream axis of the Kuroshio seems to be located at a point between St. 8 and 9, where all isotherms decline sharply toward southeast. The isotherms below 10°C undulate remarkably between St. 6 and 11, which suggests the existence of the band structure of geostrophic current across this section, *i.e.*, three branches flowing toward southwest and four branches toward northeast located alternatively in the almost whole subsurface layer.

In Fig. 3b on Obs. II, nine days after Obs. I, the highest value of 25.2°C at the sea surface of St. 10 is nearly equal to that on Obs. I. The isotherm of 24°C is situated at ca 50 m shallower than that on Obs. I offshore of St. 11 and it rises up to the very sea surface between St. 7 and 6, accompanied with a decrement of ca 2°C of the surface layer inshore of St. 6. This decrement can not be attributed to the meteorological cooling effect, since the daily mean air temperature has kept above 20°C through the period from Obs. I to Obs. II besides the highest values of water temperature on the two observations are nearly equal each other.

The inclination of isotherms below 14°C offshore of St. 4 increase to ca 250 m per 100 miles on Obs. II from ca 100 m per 100 miles on Obs. I. This increment seems to correspond to the increment of the current speed of the Kuroshio offshore of St. 4. The axis of the Kuroshio is located between St. 8 and 9, which is the same point as that on Obs. I.

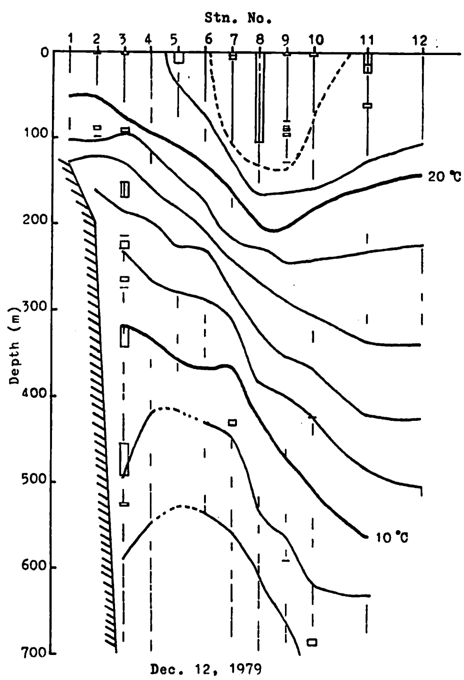
The thickness of a layer between two isotherms of 20°C and 14°C around St. 11 and 12 increases to ca 220 m on Obs. II from ca 120 m on Obs. I, which suggests an intrusion of the Subtropical Mode Water (MASUZAWA, 1969) toward the coast from the mid-ocean, while the axis of the Kuroshio still remains at the same point. Accordingly, the inclination of the isotherms between 24°C and 20°C offshore of St. 10 turns upward slightly toward southeast.

On the other hand, inshore of St. 4 all the isotherms decline toward northwest, which is quite different to that on Obs. I. The isotherms below 22°C inshore of St. 5 are situated ca 50 m shallower than those on Obs. I. These facts suggest the occurrence of the coastal upwelling accompanied with the coastal counter current.

Though the isotherms below 10°C undulate again between St. 4 and 10, the amplitude of the undulation of isotherms of 10°C and 8°C are rather small and that of 6°C seems to shift a little toward the coast.

The distinct differences of the vertical temperature field on Obs. II from Obs. I stated above, comparing Fig. 3b with Fig. 3a, are the occurrence of coastal upwelling accompanied with the coastal counter current, the intrusion of the Subtropical Mode Water toward coast, the intensification of the Kuroshio, and the decline of the undulation of isotherms, which may be attributed to the beginning of hard northwesterly blow on two days before Obs. II.

In Fig. 3c on Obs. III, five weeks after Obs. II, the highest temperature is ca 23.3°C at 10 m deep of St. 10 and the temperature of the surface mixed layer is ca 2°C lower than that on Obs. II in the whole region. This temperature fall may be attributed to the cooling effect due to cold air flow, since daily mean air temperature varies with



(c)

Fig. 3c. Vertical field of water temperature across the Kuroshio southeast off Cape Toimisaki obtained on Obs. III (12th December of 1979).

a period of six or seven days and falls down to ca 11°C on several days during five weeks from Obs. II to Obs. III.

The Subtropical Mode Water expands thick and wide. The thickness reaches to ca 300 m at St. 12 on Obs. III from ca 220 m on Obs. II and the intrusion does to St. 9 from St. 11 on Obs. II. Accordingly, the surface mixed layer has the maximum thickness more than 100 m at St. 8, where the isotherm of 20°C slopes upward toward both sides to northwest and southeast.

Beneath the Subtropical Mode Water, the inclination of the isotherms below 14°C increases further to ca 300 m per 100 miles in Obs. III from ca 250 m per 100 miles on Obs. II. This increase corresponds to the further increment of current speed of the Kuroshio. The axis of the Kuroshio seems to be located at the point between St. 7 and 8, where all the isotherms decline sharply toward southeast. It moves by ca 8 miles toward the coast, accompanied with the great intrusion of the Subtropical Mode Water.

On the other hand, the isotherms below 8°C decline toward the coast inshore of St. 5, while all isotherms on Obs. II decline inshore of St. 4. This change seems to correspond to the contraction of the coastal counter current, to only the layer below thermocline, from the whole layer. The undulation of the isotherms disappeares on Obs. III, weakening gradually with time, while it was predominant on Obs. I. The absence of undulating isotherms corresponds to rather simple current field, *i.e.*, the region of the northeastward current is dominantly wide and the counter current exists only in deep layer near the coast and in a shallow layer offshore of St. 10.

The distinct changes of the vertical temperature field during the period from Obs. II to Obs. III stated above, comparing Fig. 3c with Fig. 3b, are the great intrusion of the Subtropical Mode Water toward the coast, the movement of the Kuroshio axis toward the coast, the intensification of the Kuroshio, the descent of the coastal counter current, and the disappearance of undulating isotherms, which may be attributed to the periodic blow of hard northwesterly wind during five weeks from Obs. II to Obs. III.

4. Temperature inversion layer and isothermal layer

The temperature resolution of raw DXBT data depends slightly on the actual water temperature itself. The layer analysis, therefore, is made in this paper by fixing the temperature resolution to be 0.08°C for the whole actual temperature, since this value of 0.08°C is the maximum resolution for the observed temperature range between 26°C and 4°C. The definitions of inversion layer and isothermal layer are illustrated in Fig. 4. The resolution is fixed to be 0.08°C and the actual temperature is read at dot points shown in the left hand side of the figure. The depth interval is ca 0.5 m, depending slightly on the distance from the sea surface. It is noticed that this definition of inversion layer is slightly different from that of NAGATA (1967 a, b). The open brocks in Figs. 3a, 3b, and 3c indicate the inversion layer

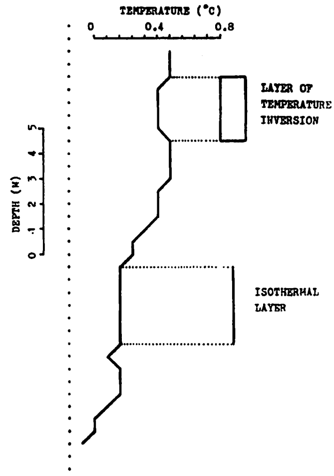


Fig. 4. Definition of the isothermal layer and the layer of temperature inversion. The resolution of water temperature is fixed to be 0.08°C and the temperature is read at dot points shown in the left hand side of which depth interval is ca 0.5 m.

with a thickness above 1 m and the bits of horizontal solid line indicate those with a thickness below 1 m. The vertical solid segments indicate the isothermal layer with a thickness above 8 m or with a vertical gradient below 0.01°C/m.

In Fig. 3a on Obs. I, many inversion layers exist in the surface layer inshore of St. 10, while only a few inversion layers in the surface layer offshore of St. 11. When the cooling processes act on the sea surface, the inversion layer develops in the top layer at first, and thereafter the isothermal layer is formed by the vertical mixing due to oceanic turbulence. Therefore the small number of the inversion layers offshore of St. 11 suggests the intense vertical mixing due to oceanic turbulence in the surface layer in this region.

However, during the period from Obs. I to Obs. II, the number of the inversion layer in the surface layer increases offshore of St. 11 and decreases inshore of St. 10. This increase of the number of inversion layers offshore of St. 11 suggests that the oceanic turbulence due to wind is rather weak in this region, compared with that inshore of St. 10, in spite of rather high value of ca 8 m/sec of daily mean wind speed at Tanegashima on the day of Obs. II. The decrease inshore of St. 10 may be attributed to the intensification of vertical mixing induced by the coastal upwelling inshore of St. 6 besides the wind effect.

In Fig. 3c on Obs. III, the number of inversion layers in the surface layer further decreases during the period from Obs. II to Obs. III. A thick inversion layer with a thickness of ca 120 m exists at St. 8, correlating with the maximum thickness of the surface layer at this point. The decrease of the number of inversion layers in the surface layer can be attributed to the vertical mixing caused by the periodical hard northwesterly blow through the period.

Beneath the surface layer, more or less larger number of inversion layers exist around the undulating isotherms below 10°C between St. 5 and 10 in Fig. 3a on Obs. I. In Fig. 3b on Obs. II, the number and thickness of inversion layers beneath the surface layer both increase, especially offshore of St. 10, while in Fig. 3c on Obs. III many inversion layers exist unexpectedly only near the coast within wide range of temperature of 20°–6°C.

In Fig. 3a, 3b, and 3c on the three observations, the isothermal layers exist anywhere in the surface layer. The thickness of the isothermal layer is the highest on the Obs. III on the average with the extreme value of ca 100 m at St. 12 on Obs. III, suggesting the occurrence of the intense vertical mixing due to the hard northwesterly blow during five weeks from Obs. II to Obs. III.

Beneath the surface layer, many isothermal layers exist also in a temperature range below 10°C on the three observations. But, the number of isothermal layers below 10°C is the highest on Obs. II instead of Obs. III.

These large variations of distributions of isothermal and inversion layers beneath the surface layer stated above may be caused by a small scale mechanism which remains to be proved.

5. Concluding remarks

The short-term variations of vertical temperature field in an ocean section across the Kuroshio southeast off Cape Toimisaki are presented, using the XBT data obtained three times during a month and a half in autumn of 1979, the first 27th October, the second 5th November, and the third 12th December.

During nine days between the first and the second observations, the large variations of the vertical temperature field take place, *i.e.*, the coastal upwelling accompanied with the coastal counter current, the intrusion of the Subtropical Mode Water toward the coast, the intensification of the Kuroshio current, the decline of the undulating isotherms beneath the surface layer, the decrement of the number of temperature inversion layer in the inshore surface layer, the increment of the number of temperature inversion layer in the offshore surface layer, the movement toward the coast of the region with many temperature inversion layers beneath the surface layer, and the increment of the isothermal layer beneath the surface layer. These large variations are suggested to be induced by the beginning of the hard northwesterly blow on 3rd November of 1979.

During five weeks between the second and the third observations, the further large variations take place, *i.e.*, the water temperature fall in the surface layer, the further intrusion of the large amount of the Subtropical Mode Water toward the coast, the further intensification of the Kuroshio current, the movement toward the coast of the stream axis of the Kuroshio, the descent of the coastal counter currents, the disappearance of the dominant undulation of the isotherms beneath the surface layer, the decrement of the number of temperature inversion layer in the surface layer, the concentration of temperature inversion layer to the coastal region beneath the surface layer, and the decrement of the number of isothermal layer beneath the surface layer. These further large variations are suggested to be induced by the weather condition during the period of five weeks, *i.e.*, the hard periodical northwesterly blow and the periodical fall of the daily mean air temperature down to ca 11°C.

It must be mentioned here that several important problems remain to be discussed, including the geostrophic current which will give us much more valuable imformation. The authors are to present elsewhere the results of the estimation of the geostrophic currents from the XBT data by means of the method proposed by EMERY (1975) and TAKANO *et. al* (1981). The theoretical considerations on the mechanism of the large variations described above are not developed in this paper. The time change of the vertical temperature field is conjectured to be explained by the baroclinic time response of the stratified ocean near the coast, accompanied with alongshore current, to the spontaneous hard wind blowing offshore, which will be made in future.

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Data Source: Monthly Weather Report in Kagoshima Prefecture, Kagoshima Branch of Japan Meteorological Association, Kagoshima. No. 10, 11 and 12 of 1979.

Appendix. Data of expendable bathythermograph, Southeast off Cape Toimisaki, Oct. 27, Nov. 5 and Dec. 12 of 1979, Keiten-maru, Kagoshima University.

St.	Date	Time	Lat.	Long.	Depth							Temperature									
		JST	N	E	0 m	10	20	30	50	75	100	125	150	200	250	300	400	500	600	700	800
1	10/27	1556	31–15.1	131–19.8	24.1	24.1	24.1	24.0	23.8	22.0	20.3	17.4	—	—	—	—	—	—	—	—	—
2		1642	31–09.0	131–26.6	24.2	24.2	23.9	24.1	23.9	22.7	20.5	17.3	15.7	—	—	—	—	—	—	—	—
3		1725	31–03.0	131–32.8	24.5	24.4	24.4	24.4	24.6	23.3	21.3	19.1	17.1	14.1	11.9	10.8	8.5	6.9	5.6	4.9	4.4
4		1805	30–56.9	131–39.3	24.7	24.4	24.4	24.4	24.4	22.1	20.1	19.0	17.7	15.6	13.0	11.0	8.8	7.5	5.8	5.1	4.4
5		1845	30–51.0	131–45.2	24.6	24.5	24.5	24.5	24.4	22.6	20.0	19.0	17.7	15.2	13.2	11.3	8.9	7.6	5.8	5.0	4.4
6		1922	30–45.5	131–52.0	24.6	24.5	24.5	24.5	24.5	22.2	20.6	19.3	17.8	15.0	13.1	11.1	8.7	7.3	5.7	5.1	4.5
7		1959	30–39.8	131–58.1	24.4	24.6	24.6	24.6	24.4	22.2	20.9	19.6	17.8	15.2	14.2	12.6	10.0	8.1	6.2	5.5	4.8
8		2036	30–34.5	132–04.8	24.9	24.9	24.9	24.7	24.1	22.1	20.5	19.1	17.6	16.0	14.7	13.0	9.7	7.5	6.2	5.1	4.6
9		2112	30–28.6	132–11.0	24.5	24.6	24.5	24.3	24.2	24.2	22.6	20.8	19.1	16.5	14.9	13.5	10.7	8.4	6.8	5.8	5.1
10		2147	30–23.6	132–17.2	24.6	24.6	24.6	24.6	24.2	24.2	23.8	21.7	19.9	16.8	15.2	13.5	10.1	7.6	5.9	4.9	4.2
11		2303	30–11.0	132–30.6	25.8	25.8	25.7	25.5	25.4	25.4	25.3	24.9	24.0	19.4	16.1	13.9	10.9	8.0	6.5	5.0	4.3
12	10/28	0006	30–00.0	132–40.1	25.8	25.9	25.8	25.8	25.4	25.1	25.1	24.8	24.6	20.2	17.5	15.0	11.2	8.8	6.8	5.4	4.5
1	11/05	2031	31–15.0	131–20.0	23.2	23.2	23.0	22.5	22.2	19.6	18.8	—	—	—	—	—	—	—	—	—	—
2		1945	31–09.0	131–26.6	22.8	22.8	22.8	22.8	22.2	19.6	17.0	16.1	15.3	—	—	—	—	—	—	—	—
3		1901	31–03.0	131–32.8	23.1	23.1	23.0	23.0	21.5	19.1	17.6	16.5	15.4	12.8	11.1	9.4	7.0	6.1	5.2	4.8	4.3
4		1813	31–56.9	131–39.2	22.8	22.8	22.8	22.4	20.2	18.4	17.1	16.6	15.3	11.7	10.4	8.9	7.1	6.2	5.3	4.4	4.1
5		1729	30–51.0	131–45.2	23.1	23.1	23.1	23.0	22.3	19.6	17.8	17.2	15.3	12.9	11.0	9.7	7.4	6.0	5.2	4.6	4.2
6		1643	30–45.8	131–52.3	23.7	23.8	23.8	23.7	23.0	21.3	20.4	17.5	15.6	12.9	11.3	9.5	7.6	6.8	5.7	5.1	4.6
7		1604	30–40.0	131–58.0	24.6	24.6	24.6	24.6	24.4	23.6	22.1	20.8	17.2	14.6	11.8	10.1	7.5	6.1	5.1	4.5	4.0
8		1525	30–34.5	132–04.8	24.7	24.7	24.7	24.7	24.2	23.9	22.7	20.9	19.8	15.1	13.7	11.1	8.5	6.4	5.2	4.4	4.0
9		1447	30–28.5	132–11.0	24.9	24.9	24.9	24.9	24.9	24.4	23.3	22.3	20.7	16.8	14.7	12.5	9.4	7.0	5.8	4.9	4.6
10		1409	30–23.0	132–17.2	25.2	25.1	25.1	25.1	24.9	24.8	24.5	23.2	21.4	17.6	14.3	12.7	9.3	7.1	5.7	4.9	4.4
11		1123	30–11.0	132–30.6	24.4	24.5	24.6	24.6	24.6	24.6	23.2	21.9	20.4	18.4	17.0	15.8	11.1	8.8	6.3	5.4	4.8
12		1020	30–00.0	132–40.2	24.9	24.9	24.9	24.9	24.9	24.8	23.9	21.0	20.1	18.8	16.5	15.6	12.7	9.9	7.1	5.7	5.1
1	12/12	2331	31–15.0	131–20.0	21.5	21.5	21.5	21.3	20.2	18.8	18.2	16.2	—	—	—	—	—	—	—	—	—
2		2251	31–09.0	131–26.6	20.9	20.9	20.9	20.9	20.3	18.6	18.2	15.7	14.1	13.0	—	—	—	—	—	—	—
3		2211	31–03.0	131–32.8	20.7	20.7	20.7	20.7	20.7	20.0	17.9	16.1	14.5	13.4	11.5	10.5	8.9	7.4	5.9	5.2	4.6
4		2134	30–57.0	131–39.3	20.7	20.7	20.7	20.7	20.5	20.3	19.1	17.8	16.2	13.7	12.5	10.8	8.3	6.3	5.4	4.8	4.4
5		2053	30–51.0	131–45.3	22.3	22.4	21.9	21.9	21.8	21.7	20.4	19.2	17.9	14.8	13.1	11.5	8.6	—	—	—	—
6		2012	30–45.5	131–52.2	22.8	22.8	22.8	22.8	22.8	22.0	21.5	20.4	19.1	16.2	13.0	11.3	9.2	6.5	—	—	—
7		1938	30–40.1	131–58.1	23.0	23.1	23.1	23.1	23.1	23.1	23.1	22.1	20.8	19.0	15.3	12.6	9.0	6.8	5.3	4.7	4.1
8		1855	30–34.5	132–04.9	22.9	23.0	23.0	23.1	23.1	23.1	23.1	23.1	22.8	20.3	16.7	14.9	11.1	8.4	6.0	5.2	4.8
9		1815	30–28.7	132–11.2	23.1	23.2	23.2	23.2	23.2	23.2	23.1	23.1	22.8	20.2	17.8	15.8	11.9	9.3	7.2	5.5	4.8
10		1738	30–23.0	132–17.3	23.2	23.3	23.3	23.3	23.3	23.1	23.0	22.8	22.6	19.1	17.6	16.1	12.9	10.3	8.3	6.7	5.2
11		1617	30–11.0	132–30.6	22.8	22.8	22.8	22.9	22.9	22.8	22.8	22.2	20.2	18.8	17.7	16.6	14.4	11.6	8.8	6.9	5.9
12		1513	29–59.9	132–39.8	22.6	22.3	22.3	22.3	22.3	22.3	22.3	20.5	19.7	18.7	17.5	16.6	14.5	12.2	—	—	—