Notes from ISC Data Users

Reported Teleseismic Phase Statistics at the ISC Over the Last Four Decades

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5

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5.1 Reported Teleseismic Phase Statistics at the ISC Over the Last Four Decades

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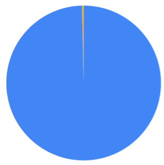
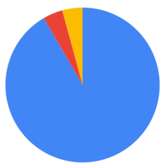
The ISC has seen a steady increase in the number of stations and phases reported over the decades (Figures 5.4 and 5.5). However, the number of teleseismic phases reported to the ISC is decreasing. Here, we will look at the statistics of all teleseismic phases reported from stations with an epicentral distance of at least 20 degrees for the time period 1970 to 2021. The purpose is to see if there have been any significant changes in the type and number of phases reported. We will be looking at time-defining phases identified by the ISC's location algorithm (ISCloc) and at the most common phase types where the ISC phase type differs from the phase originally reported. Events for which an ISC location is created typically have a magnitude larger than 3.5. For more information on how to use the ISC's data and on the Operational Procedures of the ISC, please refer to *Havskov and Lieser* (2022) and the Appendix of the Summary of the ISC (*International Seismological Centre*, 2024; available in the first issue of each volume).

5.1.1 Phase Types Identified by the ISC

Throughout the ISC's history different sets of seismic phases were used. In the beginning, only P phases were utilised for hypcentre estimations (1964 to 2000), from data year 2001 S phases were included and the current location algorithm ISCloc makes use of all IASPEI standard phases (*Storchak et al.* 2003, 2011) with a valid travel time prediction in the ak135 velocity model. This latest procedure came into full operation from data year 2011 onwards. To homogenise the ISC Bulletin, the time period from 1964 to 2010 was relocated during the Rebuild project. As part of this, the phase names reported to the ISC were reviewed, corrected and translated into distinct and standard phase names. Typical amendments included updating obsolete notations, adding missing characters, and fixing upper and lower cases. More information on the Rebuild of the ISC Bulletin can be found in *Storchak et al.* (2017, 2020).

The most common time defining phases in the Reviewed ISC Bulletin for the time period 1970 to 2021 are listed in Table 5.1 and the complete list is shown in Table S1.1 in the supplementary material. Duplicates, i.e. multiple arrivals of the same phase type at the same station are ignored and amplitude phases are not included. Figure 5.1 gives a graphical overview of the percentage of the individual phases.

Table 5.1: *The most common phases for teleseismic earthquakes used by the ISC in relocations for the period 1970 to 2021.* Used in ISC locations*: The number of phases identified and used for location (excluding duplicates).* Reported as*: Pie chart breaking down how the phase was reported to the ISC, including how often the phase was reported as such, and the next most common phase type (including duplicated reports).*

Phase	Used in ISC locations	Reported as
P	32,803,509	• P 40,735,109 (99.6%) • pP 30,626 (0.1%) • Other 123,704 (0.3%) 
PKPdf	2,537,130	• PKPdf 1,591,966 (53%) • P 1,036,401 (35%) • Other 368,241 (12%) 
PKPbc	1,100,918	• PKPbc 665,221 (53%) • P 442,679 (35%) • Other 151,450 (12%) 
PKPab	863,118	• PKPab 541,918 (56%) • P 270,168 (28%) • Other 151,277 (15%) 
PKiKP	1,872,615	• PKiKP 311,025 (14%) • P 774,039 (35%) • Other 1,153,171 (52%)  Note: 43% of PKiKP phases were reported as a PKP type phase (included in 'Other')
pP	820,015	• pP 876,259 (91%) • sP 39,488 (4%) • Other 40,807 (4%) 

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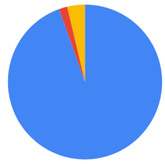
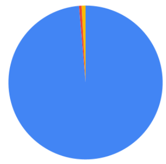
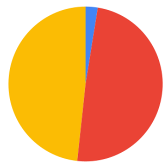
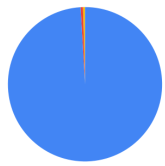
Phase	Used in ISC locations	Reported as	
PcP	723,496	• PcP 745,035 (91%) • pP 41,602 (5%) • Other 34,107 (4%)	
PP	548,485	• PP 565,838 (95%) • pP 10,385 (2%) • Other 22,338 (4%)	
Pdif	452,488	• Pdif 168,471 (31%) • P 375,623 (68%) • Other 4,403 (1%)	
S	1,651,533	• S 1,911,049 (98.6%) • SKS 10,428 (0.5%) • Other 16,116 (0.8%)	
SKSac	135,616	• SKSac 86,956 (58%) • S 48,866 (33%) • Other 13,059 (9%)	
SKiKP	34,052	• SKiKP 975 (3%) • S 18,853 (49%) • Other 18,509 (48%)	
SS	229,272	• SS 244,696 (99%) • ScS 1,224 (0.5%) • Other 1,055 (0.4%)	
sP	404,905	• sP 201,640 (43%) • pP 215,401 (46%) • Other 47,033 (10%)	
ScS	104,476	• ScS 87,340 (77%) • S 14,535 (13%) • Other 11,630 (10%)	

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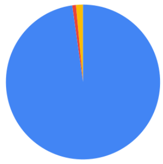
Phase	Used in ISC locations	Reported as
ScP	199,327	• ScP 217,626 (98%) • SS 1,730 (1%) • Other 3,285 (1%) 

From the table it can clearly be seen that it is a common practice to label the first arrival as P, irrespective of it being a P phase or a teleseismic core phase. A large amount of PKPdf/bc/ab, PKiKP and Pdif phases, have been reported as P and while PKP phase types were mostly reported as such (53% to 56%), the majority of PKiKP (87%) and Pdif (69%) phases were originally reported as P phases or "Other" to the ISC. Secondary phases (S, pP, PP and PcP, ScP, sP, SS) have nearly all been reported with the correct phase type (over 95%). When reporting secondary phases, a common practice is to use epicentre locations and travel time tables to identify phases. However, even then it can be difficult to distinguish the different P phases while pP and PcP are easier to identify; this may explain why they have been correctly reported more often. This is the case for S type phases as well where many SKSac, Sdif and SKiKP phases were reported as S phases. It seems that agencies assign the general type of phase rather than the specific type for convenience when picking only one or two phases.

ISCloc can re-interpret phases in every distance range, e.g. P phases can become Pn, Pb, Pg, PP, PnPn, PKiKP, Pdif, PcP, PKP(ab/bc/df) etc. as well as depth phases, with a similar list of allowed re-interpretation for S phases. There are certain additional rules that are followed, e.g. depth phases cannot be set as first arrivals by ISCloc and P phases cannot be renamed as S phases (*Havskov and Lieser*, 2022).

There are 45.5 million identified time-defining phases and the first 10 phase types in the list make up 95% of the phases. The P phases dominate with 72% of the time defining phases identified as P and including other first arrival P phase types, such as PKPdf, PKiKP, PKPbc, PKPab, and Pdif, 87% of all time defining phases (Figure 5.1). On average over the recent time period from 2010 to 2021, 19 phase types are reported less than once a month and 28 types less than 10 times per month while there are typically 119,262 P phases per month, see supplementary material.

5.1.2 Time Statistics of Number of Phases

Figure 5.2 shows the number of teleseismic phases per year for P and S. There has been a steady increase in number of phases since 1970. It seems that until the year 2000, the number of S phases did not increase as much as the number of P phases and a drop in reported S phases can be observed in the most recent years. We will look into this in more detail in Figure 5.6. Figure 5.3(a) shows the monthly number of P and P-type phases and Figure 5.3(b) shows the monthly median over a year.

The two curves are correlated, however, the median curve is smoother and better displays the overall trend of the average amount of reported P phases per year without the outliers caused by major earthquakes. The relatively high activity in 1995-1996 that is clearly observed in both curves is due to the establishment and testing of the prototype of the International Data Center (IDC) for the Comprehensive Test-Ban Treaty (CTBT). The IDC came into full operation from 2000.

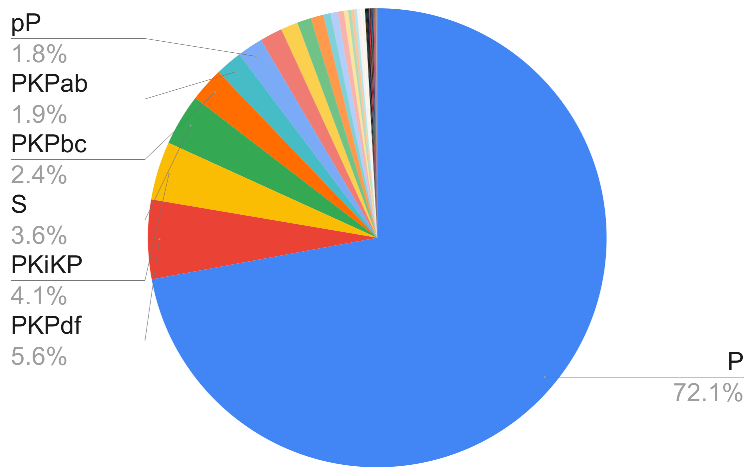


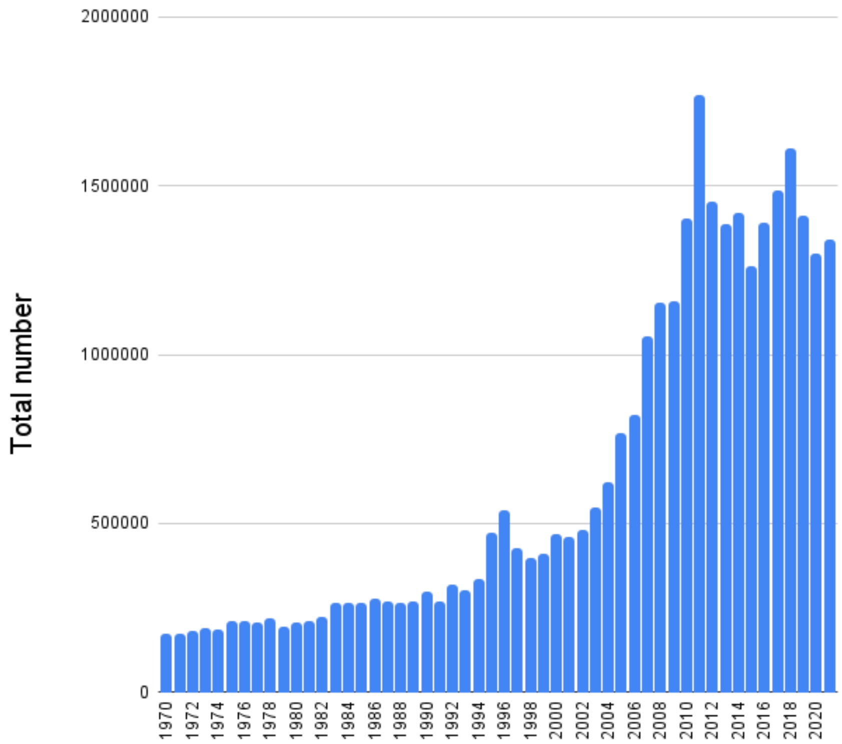
Figure 5.1: *Distribution of time defining phase types as listed in the supplementary material.*

The largest monthly number of P phases (483,514) was in March 2011 and is related to the Tohoku sequence whose main shock (Mw=9.1) triggered a destructive tsunami. It was the largest earthquake ever recorded in Japan and among the four largest in the world since 1900. The spike in December 2004 is related to another large earthquake that was one of the four largest recorded and that triggered a devastating tsunami: the Mw 9.2 Sumatra, Indonesia earthquake. Many other spikes are also related to major events (e.g. the Mw 8.8 Maule, Chile, earthquake in February 2010, the Mw 8.1 and Mw 7.7 sequence in Iquique, Chile in April 2014, the Mw 7.9 earthquake in Alaska in May 1986 etc.). From this plot it can thus be seen that in general spikes are not due to uneven reporting.

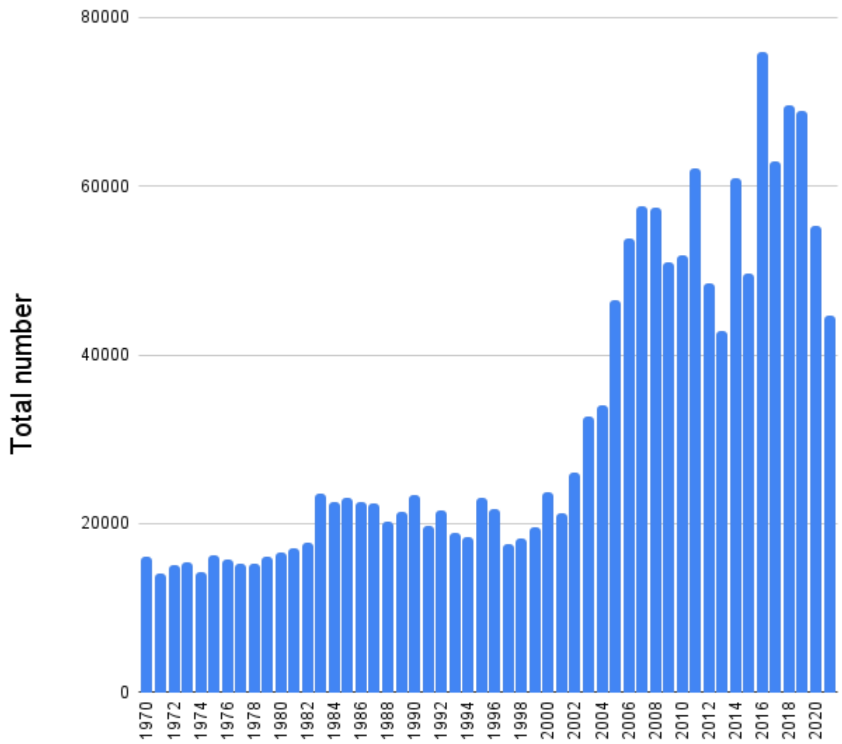
Figures 5.2(a) and 5.2(b) show a constant number of phase reports from 2010 and onward, while Figure 5.4 shows an increasing number of phases until 2015 and then a consistent number of phases reported. This difference may be a result of the total number of reported phases including data from local networks and small events. Figure 5.4 also shows that variation in amplitude reporting is correlated with the variation in phase reporting. In order to investigate if the number of reports is related to the number of stations reporting to the ISC, the number of stations reporting has been plotted in Figure 5.5.

As can be seen, there has been a steady increase in the number of stations reported to the ISC until 2018. This correlates with the increase in the total number of phases until 2018, again this might reflect the inclusion of many phases from local networks and small events. For the teleseismic phases there is no increase after 2010 despite the number of stations increasing. This is likely a result of the increased number of stations not being reported teleseismically or that the stations do not report all phases and only pick first arrivals. The sudden increase in seismic stations from data year 2021 can be explained by the implementation of the IASPEI station coding standard ADSL (Agency.Deployment.Station.Location) at the ISC. Before, only stations registered in the International Station Registry (FDSN network code IR), maintained by the ISC, could be used. Now, stations that are not registered in IR but registered with FDSN using a different network code can be used.

In order to better visualise the reporting of different phases as a function of time, the number of reported phases for selected phase types relative to the number of P phases is calculated (Figure 5.6). The purpose is to check if more P phases also result in a similar increase in the number of other common secondary

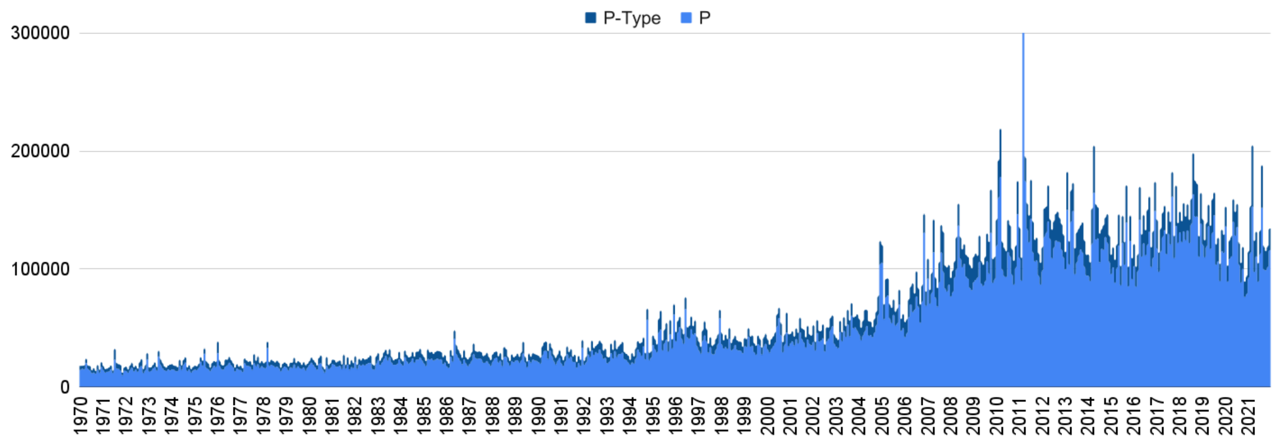


(a) P phases

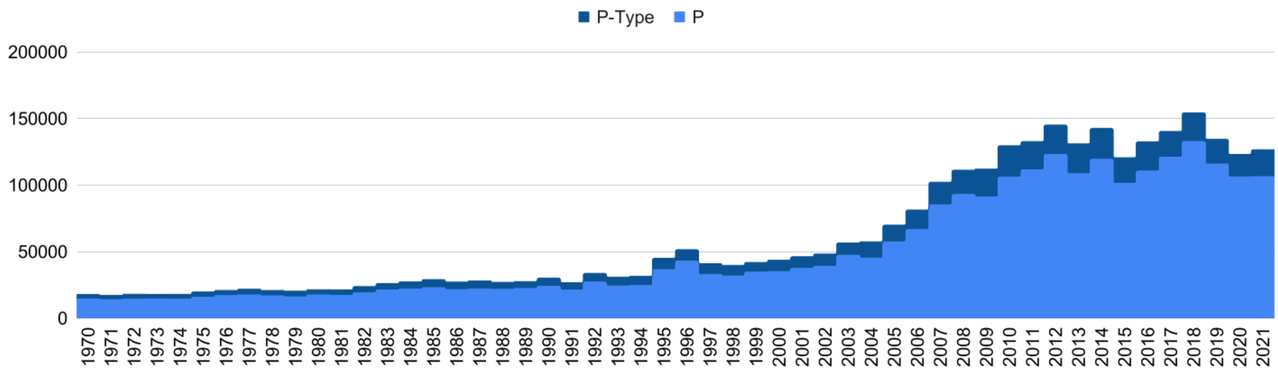


(b) S phases

Figure 5.2: *Number of teleseismic P and S phases used in ISC locations per year.*



(a) Monthly number of teleseismic phases. The peak in 2011 extends to 483,514 and relates to the Tohoku event.



(b) Yearly median of teleseismic phases.

Figure 5.3: *Stacked bar chart of teleseismic P and P type (PKiKP, PKPab/df/bc, Pdif) phase arrivals.*

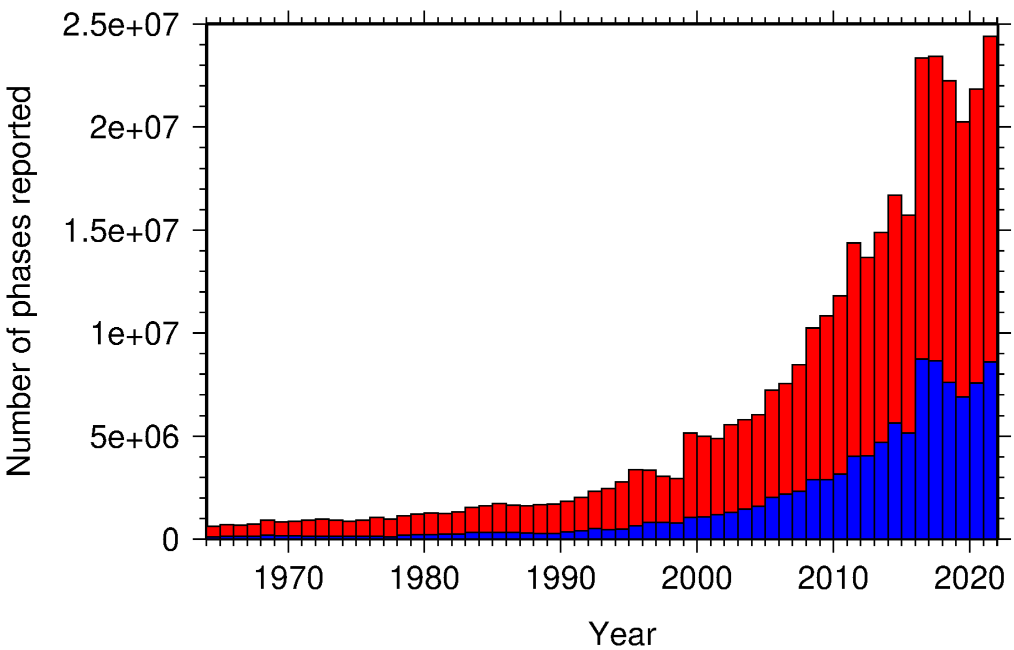


Figure 5.4: *Histogram showing the yearly number of phases (red) and number of amplitudes (blue) collected by the ISC from 1964 to 2021. The number of phases and amplitudes is the total number from all events (local and teleseismic) and includes duplicates.*

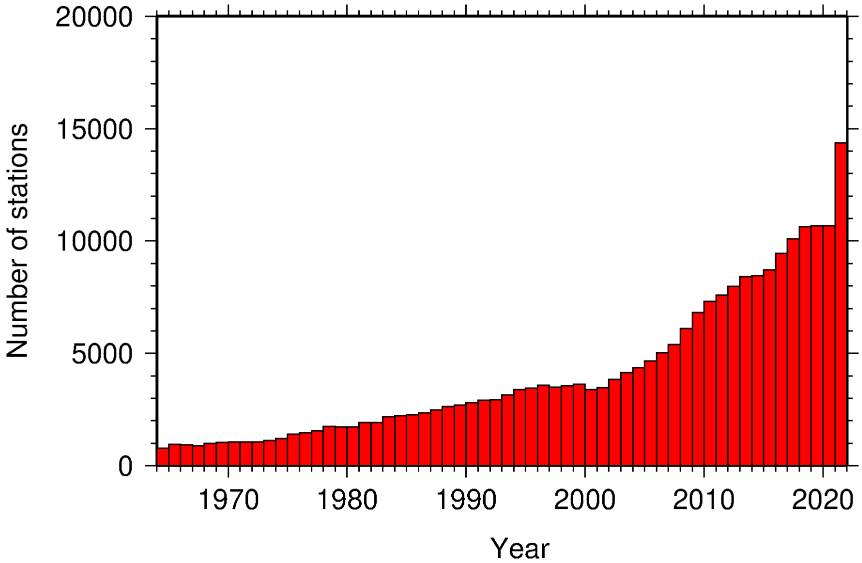


Figure 5.5: *Histogram showing the number of stations reporting to the ISC per year from 1964 to 2021.*

phases. The phases selected are S, PcP, PP, SS, pP, sP, ScS and ScP and it is assumed that most of these phases have been reported as such to the ISC. As seen from Table 5.1, this seems to be the case at least for phases S, PcP and pP.

For all phase types, except SS, PcP and ScP, the number of secondary phases relative to the number of P phases has declined overall with time, e.g. before 1990, there were twice as many S phases relative to the number of P phases as compared to 2021. Until the year 2000, the number of S phases (Figure 5.2(b)) remained relatively stable before increasing around 2000. However, this increase is less than the rise in P phase reports and thus the relative number decreased in recent years which unfortunately can impair depth determination.

All the plots have time periods with prominent peaks, e.g. for ScS around 1990. Since there is no similar decline in the number of P phases, it can be concluded that relatively more ScS readings were reported around 1990. The different phase types have peaks in different time periods and there does not seem to be a similar decline in number of P phases which could explain the peaks. It therefore seems likely that the change in the relative number of phases is caused by changes in reporting of these phases before 2010. After 2010, the number of P phases remained fairly stable (Figures 5.2 and 5.3) and the relative number of other phases has also remained stable, indicating that picking practice has not changed much since 2010.

As an example, the absolute number of pP and sP phases is shown in Figure 5.7. It can be seen that after approximately 2008, there is a clear reduction in the number of depth phases even though the number of P phases has not declined. The reduction in depth phases has a negative impact for the accuracy of the hypocentral depths. To remedy this, the ISC from data year 2016 onwards picks teleseismically observed depth phases from freely available waveforms from global seismic networks. The impact of this activity can be clearly seen in the increase of depth phases from 2016 onward in Figure 5.7. However, the number of depth phases still remains below the peak observed for 2000-2010.

A lack of secondary phases in reports to the ISC has been observed before (e.g. *Bormann*, 2013). Between 1974 and 1984, the first S-wave arrivals were reported on average to the ISC about twenty

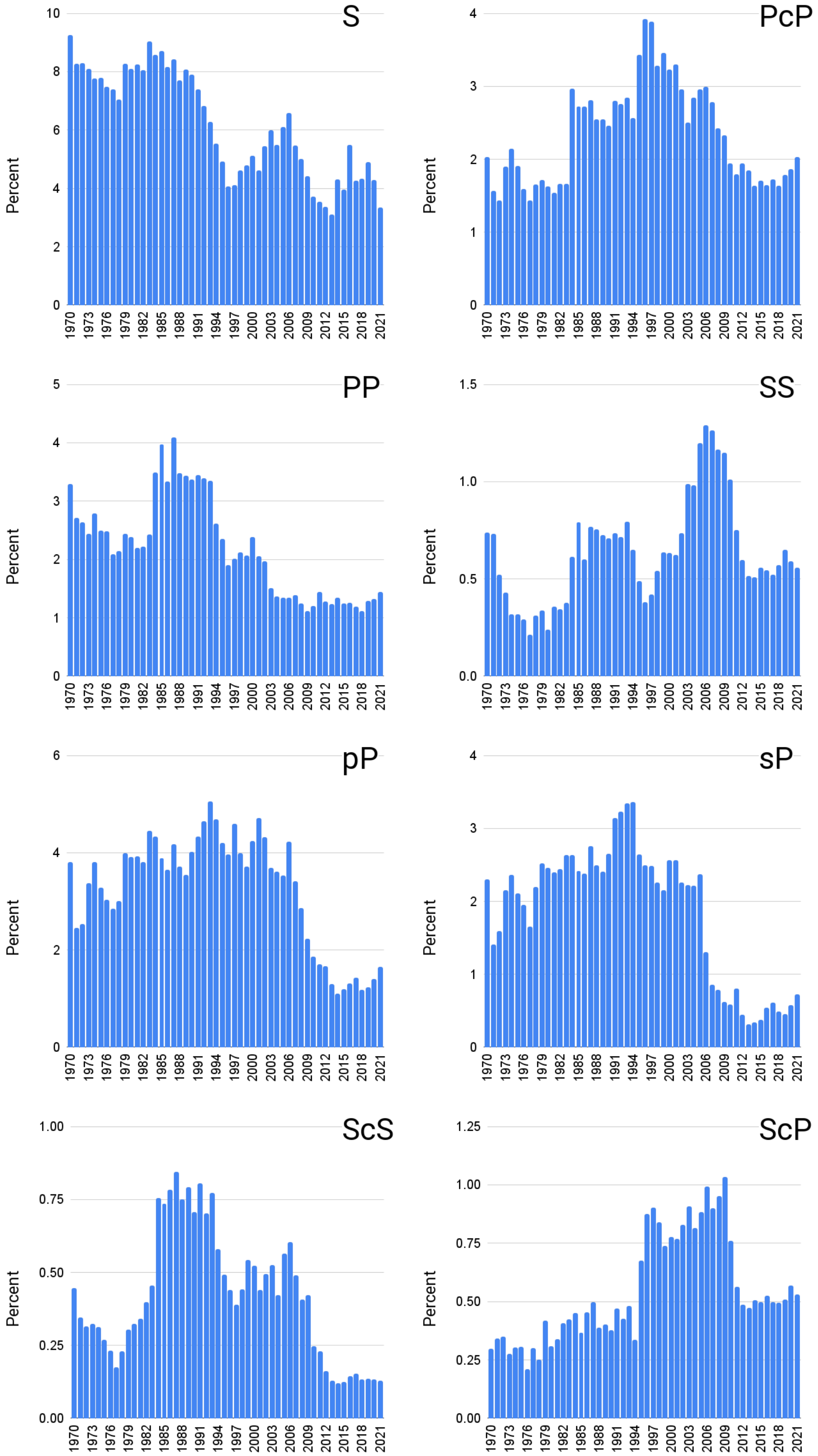


Figure 5.6: *Ratio of number of phases of each type relative to number of P phases in percent. Teleseismic phases used in ISC locations are shown.*

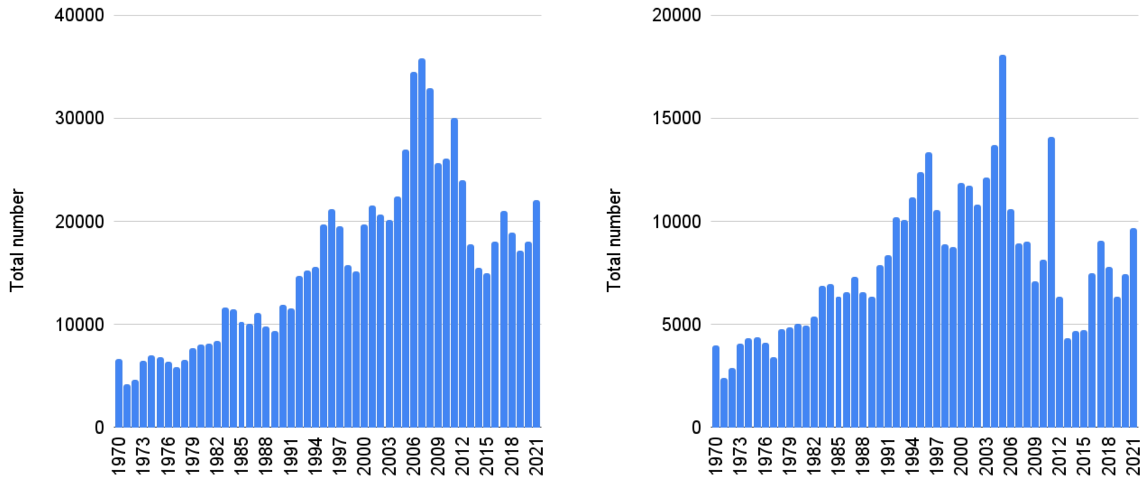


Figure 5.7: *Yearly total number of teleseismic pP (left) and sP (right) phases used in ISC locations.*

times less frequently than P. For teleseismic phases used in ISC locations, we observe about 13 times less for the same period and down to 25 times in current times.

5.1.3 Discussion

The number of stations worldwide that are reported to the ISC has increased steadily since 1964 and particularly since 2019. However, the reporting of teleseismic phases has not followed this trend. This is particularly apparent between 2010 and 2021 where the number of stations reporting has almost doubled but the absolute number of P phases has kept nearly constant. This could indicate that, despite the number of stations in a network increasing, phases are reported on the same number of stations or fewer. It is particularly noticeable that reporting of secondary phases has sharply declined since 2010. One explanation for this is that it is more time consuming to manually pick secondary phases than only P phases.

At the same time modern networks are more capable of producing reliable secondary teleseismic picks. In the travel time plot of 2010-2021 in Figure 5.8, the secondary phases cover a much wider range of epicentral distances than in the earlier time period because they can be better recorded and identified with advanced modern equipment and processing software (eg. PKiKP, PKKP, PKPPKP).

Figure 5.9 shows the average number of local agencies per event reporting teleseismic phases. Global agencies have been excluded (NEIC, MOS, IRIS and IDC) from this plot. From data year 2013 to 2019 fewer agencies reported teleseismic phases, however, there has been a slight increase in the number of reporters since the nadir in 2018-2019. This is most likely due to the change to the ADSL data format, as more stations became available. In addition, the ISC started a project in 2019 dedicated to filling a notable gap in teleseismic data coverage by picking teleseismic phases, particularly from African stations.

The decline in the number of reporting agencies per event may indicate that fewer agencies are picking teleseismic phases. Temporary networks for a local study may not process data that is not considered relevant to their study. The prevailing reasons may be that these networks are designed for local studies, and that they do not have the time, funding, staff, or feel an obligation to report teleseismic events. This

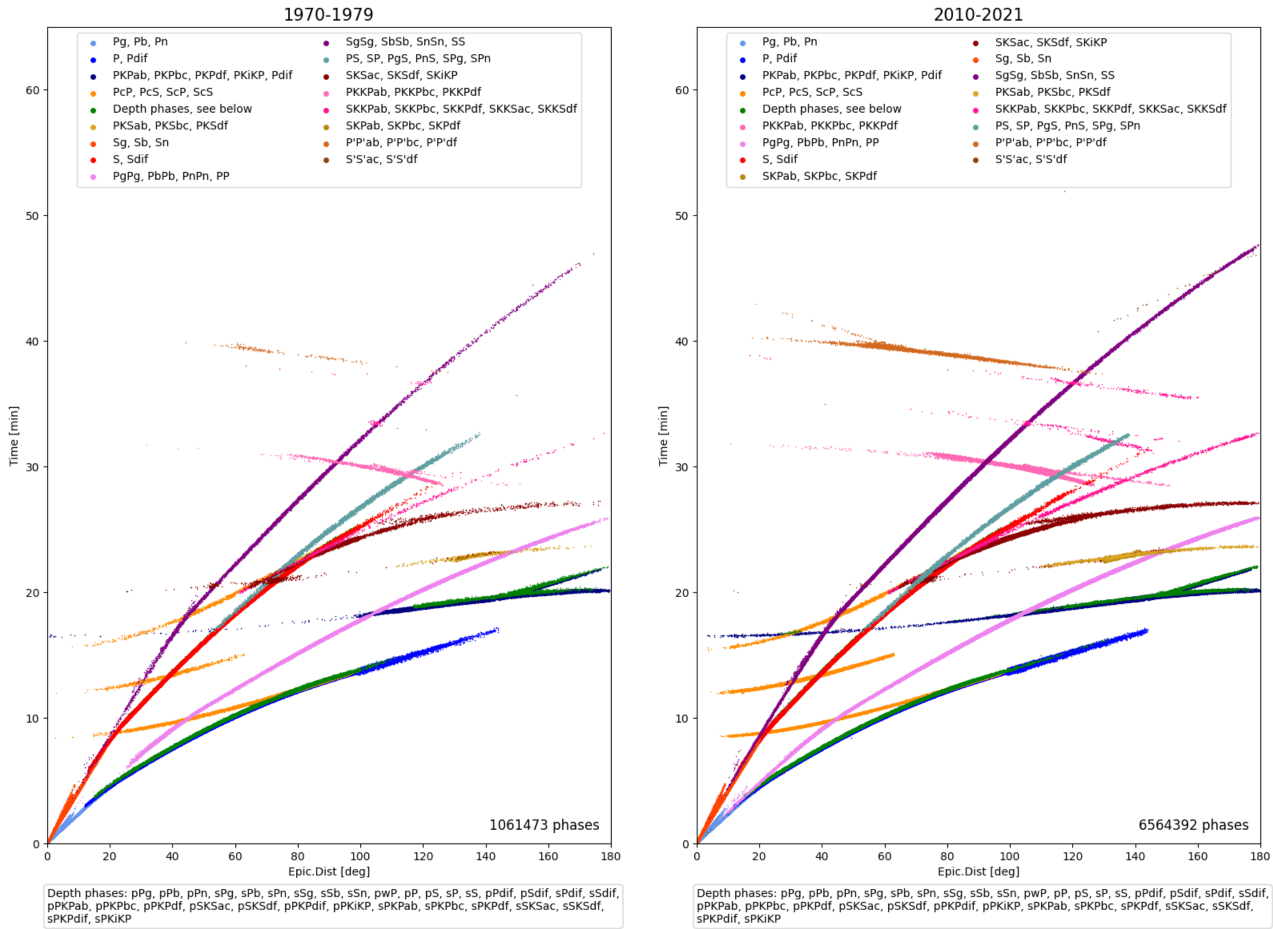


Figure 5.8: *Travel time plots of time defining phases used in ISC locations of events with a magnitude larger than 5.5 and with a depth less than 35 km from the 1970s compared to 2010-2021.*

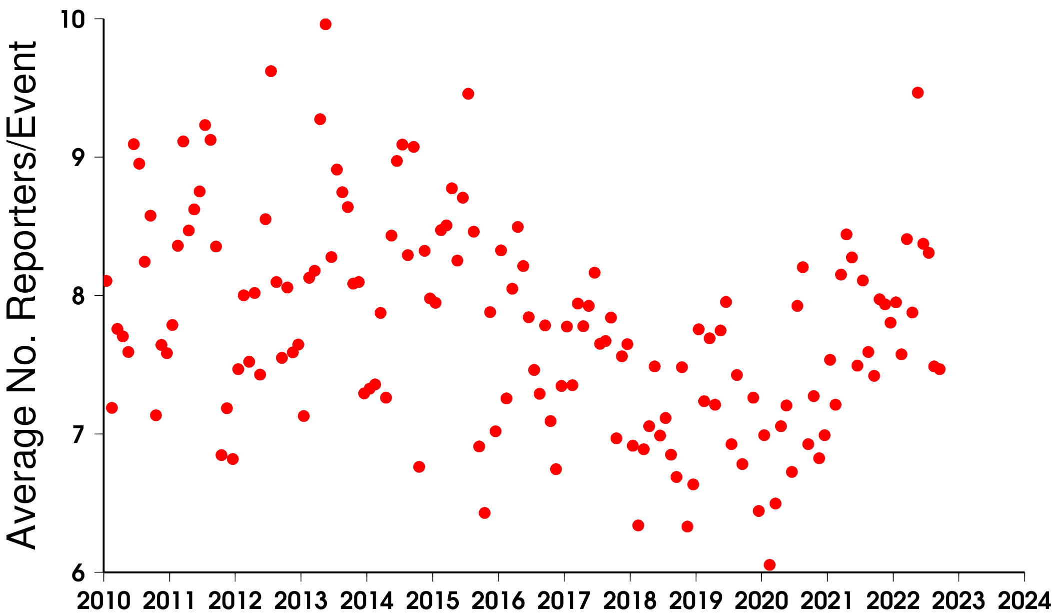


Figure 5.9: *Monthly average number of agencies per event for recent years reporting teleseismic phases, including ISC. Agencies reporting global data (NEIC, MOS, IRIS and IDC) have been excluded.*

issue even extends to some national networks in countries with established programmes in seismology which have stopped reporting teleseismic events. They report that it is too time consuming to continue picking teleseismic events despite having a long tradition of doing so. These issues seem to be reflected in Figure 5.9, some expanding networks may have chosen to only report the largest teleseismic events and only for a select number of stations. Fortunately, many seismic stations share waveform data with other countries, and thus reports at these stations are still made. However, this can result in data duplication while not improving the station coverage for the event and this is failing to reverse the decline in reporting of teleseismic phases.

Another reason for reading less teleseismic events might be related to the way the data is processed. Some networks are set up to primarily trigger for local and regional events and the processing is geared towards these events. In these cases the teleseismic data would not enter the data stream for manual processing. Since the triggers might be used for automated alerts, there is a risk that teleseismic events might generate false local events due to the limited extent of the local network.

Further, both the decrease in secondary phases relative to first arrivals and the reduced number of agencies reporting teleseismic phases could be caused by the rise of automatic and machine learning phase pickers that mostly focus on P and S phases for local seismicity. The ISC does not include fully automatic picks, (that it is aware of). In reality, the phases reported as manual phases are likely to be an unknown mix of manual, automatic reviewed picks and unreviewed automated picks.

Another reason for the decline may be that the current generation of seismologists have not been exposed to teleseismic observations as much as older generations of seismologists were and therefore do not see the importance of teleseismic data.

As we have detailed above, there are many potential explanations for the decline in the reporting of secondary phases and for the stagnation of reporting of teleseismic P phases. While we acknowledge that it may be a challenge for local agencies to include teleseismic first or secondary phases in their routine procedures, we encourage them to pick and report teleseismic arrivals on selected stations for moderate to large events. This will benefit the whole seismological community and ensure that we are making the best use of the enhanced networks that are available today.

5.1.4 Conclusion

- Reporting of teleseismic P phases has had a steady increase from 1970 until 2010. After 2010 the number of teleseismic P phases per year seems to be constant.
- A lot of the P type phases (P, PKiKP, PKPab/df/bc, Pdif) are mostly reported as P.
- The number of the phases S, PcP, PP, SS, pP, sP, ScS and ScP relative to the number of P phases has seen large variations over the years indicating changing picking practices.
- For all phases except SS, PcP and ScP, the relative and for some also the absolute number of reported phases is at the lowest level compared to any period before.
- We encourage more agencies to pick teleseismic first and secondary phases.

Acknowledgements

We thank James Harris for his efforts in extracting the data for this study from the vast ISC database.

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Supplementary Material

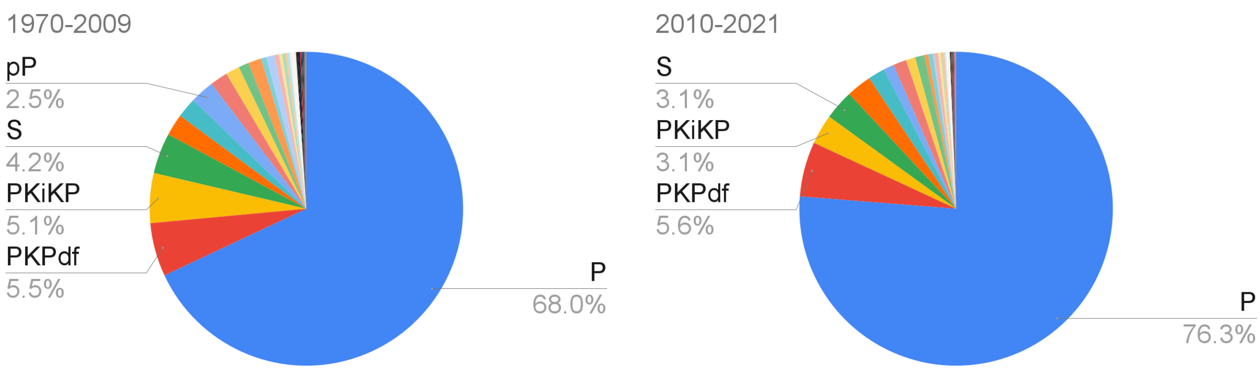

Figure S1.1: *Pie charts of reported phases in different time intervals shown in Table S1.1*

Table S1.1: *Total number of phase types reported and monthly average in different time intervals.*

Phase	Total number	Average number of phases per month		
	1970-2021	1970 – 2021	1970 – 2009	2010 – 2021
P	32,803,509	52,569.73	32,561.91	119,262.43
PKPdf	2,537,130	4,065.91	2,637.00	8,828.97
PKiKP	1,872,615	3,000.99	2,457.82	4,811.54
S	1,651,533	2,646.69	2,001.10	4,798.66
PKPbc	1,100,918	1,764.29	1,075.66	4,059.74
PKPab	863,118	1,383.20	982.78	2,717.94
pP	820,015	1,314.13	1,203.20	1,683.90
PcP	723,496	1,159.45	868.71	2,128.58
PP	548,485	878.98	687.59	1,516.97
Pdif	452,448	725.08	497.18	1,484.74
sP	404,905	648.89	656.92	622.12
SS	229,272	367.42	257.63	733.41
pwP	228,234	365.76	410.20	217.63
ScP	199,327	319.43	225.07	633.97
SKSac	135,616	217.33	151.90	435.45
ScS	104,476	167.43	162.89	182.56
PKKPbc	93,401	149.68	84.00	368.61
pPKPdf	84,395	135.25	125.88	166.49
SnSn	52,689	84.44	58.16	172.01
sS	49,871	79.92	70.39	111.69
PnPn	45,384	72.73	48.45	153.67
SKPbc	35,928	57.58	26.65	160.67
PcS	35,895	57.52	57.89	56.30
pPKPab	34,874	55.89	50.87	72.60
SKiKP	34,052	54.57	42.31	95.44
PnS	33,656	53.94	61.51	28.69
PS	31,895	51.11	47.59	62.87
sPKPdf	28,929	46.36	46.05	47.41
SKKSac	26,970	43.22	38.83	57.85
pPKPbc	25,597	41.02	32.05	70.92
PKKPab	25,152	40.31	24.43	93.23
SKSdf	24,795	39.74	31.77	66.30
PKSdf	22,771	36.49	33.69	45.82
PKKPdf	22,112	35.44	21.13	83.13
P'P'df	15,239	24.42	3.26	94.97
sPKPab	13,080	20.96	20.84	21.38
SP	11,811	18.93	16.67	26.47
SKPab	11,686	18.73	11.64	42.37
sPKPbc	10,827	17.35	16.19	21.21
SPn	7,323	11.74	14.19	3.54
SKPdf	6,671	10.69	3.50	34.65
pS	6,372	10.21	9.40	12.92
Sdif	5,879	9.42	5.73	21.72
Pn	5,376	8.62	6.98	14.06
pPdif	4,219	6.76	5.58	10.71
SKKPbc	3,723	5.97	2.72	16.80
pPKiKP	3,239	5.19	3.37	11.27
sPKiKP	2,064	3.31	3.81	1.65
SKKSdf	1,706	2.73	1.17	7.94
sPdif	1,659	2.66	2.44	3.40
P'P'bc	1,448	2.32	0.26	9.19
P'P'ab	880	1.41	0.79	3.47
SKKPab	657	1.05	0.38	3.31
PKSbc	574	0.92	0.81	1.28
SKKPdf	371	0.59	0.09	2.28
Sn	320	0.51	0.50	0.54
PKSab	259	0.42	0.32	0.72
sSKSac	197	0.32	0.26	0.51
S'S'ac	119	0.19	0.09	0.51
pSKSac	101	0.16	0.16	0.17
sSdif	82	0.13	0.06	0.36
PKKSbc	30	0.05	0.01	0.16
SPg	29	0.05	0.06	0.01
PgS	26	0.04	0.03	0.07
sSKSdf	25	0.04	0.04	0.05
PKKSdf	24	0.04	0.01	0.13
pSdif	23	0.04	0.05	0.01
pSKSdf	8	0.01	0.01	0.03
S'S'df	5	0.01	0.01	0.01
PKKSab	5	0.01	0.01	0.00
sPn	5	0.01	0.01	0.01
pPn	4	0.01	0.00	0.01
sSn	4	0.01	0.00	0.01
Pb	1	0.00	0.00	0.01