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A Survey of Recent Changes in the Main Components of the Ocean Tide

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Abstract

Changes in the ocean tide during the 20th century have been reported for several parts of the world by different authors. However, it has not always been clear whether the observed changes have been local or regional in scale. This paper reports on a survey of tidal changes in recent decades using a quasi-global data set of tide gauge information. Little evidence has been found in Europe or the Far East (including Australasia and Asia) for the extensive regional changes to the main tidal constituents reported recently for N America. However, evidence for change in smaller regions can be identified wherever the density of tide gauge information allows. Therefore, it seems that tidal changes may be commonplace around the world, although not necessarily with large spatial scales. All of the reported changes have been difficult to explain. However, it is hoped that quasi-global surveys such as the present one may eventually provide further insights.

Keywords: Ocean Tides; Sea Level Variations; Decadal Ocean Variability

1. Introduction

Changes in mean sea level have been the subject of much recent research owing to their association with climate change (Bindoff et al., 2007). Changes in extreme sea levels, and the consequent changes in flood risk, have also been investigated in some detail (Lowe et al., 2010). In most of these studies, the ocean tide is regarded as having undergone little change and, it is assumed, will not change significantly over the next few decades.

However, it seems that there were indeed measurable changes in the ocean tide during the 20th and early 21st centuries, that at some locations were comparable to those in the mean level. The observed changes have not been confined to particular stations, or localised estuaries or bays, but have occurred over large sections of the world coastline. In most cases, the changes are not understood and require further investigation. Amongst recent papers, Ray (2006, 2009) has pointed to increases in the amplitude of the M_2 tide in the near-resonant Gulf of Maine and along most of the NE American coast, and also to considerably larger (in percentage terms) decreases in S_2 amplitude. At certain American Atlantic stations the S_2 amplitude has exhibited a negative trend exceeding 10% per century (0.1% per year). Jay (2009) described changes along the Pacific coasts of N and S America with increases in amplitude of order 2% per century (0.02% per year) in both semi-diurnal and diurnal bands for stations north of 18° N. These recent regional studies have presented a more comprehensive overview of tidal change than most made previously which tended to concentrate on records from individual countries or locations (e.g. Woodworth et al., 1991 for the UK, and references therein relating to neighbouring European countries; Flick et al., 2003 for the USA; Hollebrandse, 2005 for the Netherlands).

The purpose of the present paper is to present a survey of the extent of recent tidal changes by making use of a quasi-global sea level data set, with the aim of the tidal community deriving further insights from them. The GESLA (Global Extreme Sea Level Analysis) data set was compiled through a collaborative activity of the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC), Australia and the National Oceanography Centre (NOC), Liverpool, UK in order to study variations in extreme sea levels (e.g. Menéndez and Woodworth, 2010). However, it also provides what is probably at the present time the best source of information on regional and large-scale tidal changes.

The GESLA data set consists of 675 separate sea level records, with many duplicates, obtained from the archives of the University of Hawaii Sea Level Center (UHSLC, uhslc.soest.hawaii.edu), the Global Sea Level Observing System (GLOSS) Delayed Mode centre (www.gloss-sealevel.org), and a number of national data centres. Its focus is on providing information on extreme sea levels in recent decades. As a consequence, while it has useful spatial coverage for the 1970s onwards, it contains only a small number of records that span most of the 20th century. It is our intention that future versions of the data set will contain a larger number of long records. However, in the meantime, the analysis presented below demonstrates how the shorter records may be used to provide insight into century-timescale tidal changes, on at least a data set-average, if not an individual station, basis.

2. Methods

In this study, we concentrate on the 2 main semi-diurnal (M_2 and S_2) and diurnal (K_1 and O_1) components of the ocean tide. S_2 differs from the other constituents in being 'radiational' as well as gravitational in origin (Cartwright, 1977; Pugh, 1987). The amplitudes and phase lags of each constituent were obtained from analysis of separate calendar years of data using the NOC Tidal Analysis Software Kit (TASK, Bell et al., 1996), selecting only those years of data for which tidal measurements were at least 75% complete. For a one-year analysis, TASK assumes equilibrium tide relationships between a tidal harmonic and its nodal (18.61 year) sidebands. That is to say, it assumes an approximately 3.7, 0.0, 12 and 19% variation in amplitude (this is usually referred to as the nodal factor 'f'), and approximately 2.1, 0.0, 9 and 11 degrees variation in phase lag (nodal factor 'u'), over 18.61 years for M_2, S_2, K_1 and O_1 respectively (Doodson and Warburg, 1941). Consequently, any real non-equilibrium relationship will result in an apparent 18.61 years variation in harmonic 'constants' (amplitudes and phase lags) due to the imperfect nodal parameterization, and that apparent variation (which we denote as 'residual variation' below) could be misinterpreted in a short record as a secular trend in the tidal constants.

Each time series of amplitude or phase lag derived from the annual analyses of each tide gauge record was parameterized in terms of an 18.61 year sinusoidal cycle plus a secular trend, the former to account for any residual (non-equilibrium) nodal component. Four parameters were obtained from these linear regressions:

1. The rate of change of the amplitude of the constituent expressed as a percentage change per year (RPA).
2. The rate of change of the phase lag of the constituent expressed in degrees per year (RPL).
3. The amplitude of the residual nodal variation expressed as a percentage of the mean amplitude (PNOD).
4. An integer (NSIGN) which flags whether the residual nodal variation peaks closer to *N* (the mean longitude of the lunar ascending node) equal to 0° rather than to *N* equal to 180° (i.e. whether any residual nodal variation peaks closer to 1950.62 ± n 18.61 rather than in between); NSIGN is defined as -1 and +1 respectively.

As a check on the method, parameterizations were made to time series for stations reported by Woodworth et al. (1991), Araújo and Pugh (2008), Ray (2006, 2009) and Jay (2009) using the same spans of data employed by those authors. In each case, almost identical findings were obtained for trends in tidal constants and, in the case of Ray (2006), for the amplitude of nodal variations.

(A reviewer has pointed out correctly that an alternative approach would be to conduct first a tidal analysis of all the data in each record, thereby determining empirical average nodal ‘f’ and ‘u’ factors which can be applied subsequently to each separate annual tidal analysis cf. Foreman and Neufeld (1991). Such an approach should lead to similar conclusions on trends in amplitudes and phase lags.)

In order to obtain an optimum spatial coverage of observations of tidal change from the GESLA data set, it was necessary to make use of many of the records which span only the last few decades.

Findings based on these shorter records were validated with the use of the long records in the data set, by performing one analysis over the entire record length and a second analysis over a shorter period. In this way, notwithstanding the undoubtedly valid observations of Ray (2009) that trends in tidal constants can themselves have a temporal dependence, the suitability of the shorter records to provide information relevant to century timescale trends can be tested. In addition, the ability of the shorter records to determine reliable nodal (18.61 year) parameters from as little as 30 years of data can be determined.

Consequently, subset A of the data set was defined, consisting of 83 long records with at least 50 years of information and with any start and end date of the record allowed (the earliest start date being 1846 and the latest 1955). Then, subset B was defined, consisting of 220 records with at least 30 years of information starting in 1950 or later. Subset A is dominated by the long N American records discussed by Ray (2006, 2009) and Jay (2009), with relatively few from outside the Americas. Nevertheless, the origin of the records should not be a critical factor in a test of methods.

Values of RPA, RPL and PNOD were selected for a constituent from each subset only if they were considered to be meaningful, which meant that: (i) the time series of amplitudes or phase lags contained no large outliers (defined as more than 30% and 20 degrees respectively) and (ii) the average amplitude of the constituent was larger than a certain threshold (5 cm for M_2 and 2.5 cm for the other constituents). The second test was applied as, in low tidal amplitude areas, the records will contain relatively larger amounts of non-tidal variability and conclusions on tidal change may be more difficult to arrive at. The result of applying these requirements to the time series of each constituent is that a slightly different number of subset-pairs were selected for each constituent and parameter.

Figure 1 presents the measured trends in percentage amplitude (RPA) from stations in subset A, using all their data or only that part of their records which would be included in subset B. Although some stations yield very different trends with the two selection criteria, most demonstrate similar values, with correlation coefficients between RPA values from the two subsets given in Table 1. One observes that the highest correlation is obtained for S2, although it is difficult to assign a reason for that. A similar correspondence is obtained for trend in phase lag (RPL, Figure 2, Table 1) and percentage nodal amplitude (PNOD, Figure 3, Table 1). There is good agreement for the latter for both small and large residual nodal variations. The similarity of findings shown by these figures demonstrates that the shorter subset B criteria are capable, in most if not all cases, of providing information on secular tidal change on timescales comparable to those records in subset A (i.e. century timescales).

Table 2 shows the number of occasions on which the same or different value of NSIGN was obtained from the subset-pairs. The number with the same sign can be seen to be considerably in excess of those with different sign. Table 2 also shows, for pairs with the same NSIGN, how many have values of +1 or -1. In the case of S_2, it is interesting that most have NSIGN=-1, indicating maximum S_2 amplitude at N=0 when M_2 amplitude is minimum.

Given that the above tests provide confidence in the use of the shorter records, one can progress to make use of all subset B records to study spatial variations in each tidal parameter. However, prior to that investigation, it was necessary to remove duplicate information which originated from a number of records in the GESLA data set having been obtained for the same stations but from different sources. The duplicate removal criteria rejected a record if it was shorter than another from the same station (after application of the selection criteria A or B), or, if record lengths were the same, the record with the larger standard error on the fitted trend was rejected. For a small number of stations, the data set contains 3 or more records, and the duplicate removal criteria were applied iteratively such that only one record survived for each station. After duplicate removal, 67 records remained in subset A with average length 77.4 years, while 176 records remained in subset B with average length 43.3 years.

3. Results

In this section, we concentrate on findings from three regions (N America, Europe and the 'Far East' which includes Australasia and Asia) as they contain the majority of records in the data set. (Additional figures and tables of parameters may be found in the Author Archive of the Permanent Service for Mean Sea Level, www.psmsl.org/products/author_archive/). We present first the values of the four parameters obtained from the regression fits for the stations in each region, and then discuss the significance of the findings.

Figures 4-6 (a,b) shows subset B findings for RPA and RPL for the four constituents for stations in N America, Europe and the Far East respectively. Positive and negative trends from records which satisfy the requirements (i-ii) given above are shown in red and blue respectively. Stations shown by a small black do not satisfy one or both of the requirements. Most of these are in the low tidal amplitude areas which fail requirement (ii).

Figure 4(a) reproduces the strong negative trends in S_2 amplitudes on the Atlantic coast discussed by Ray (2009), with the use of longer records in his case. Such changes are considerably in excess (in percentage terms) of those reported for M_2 which tend to be of opposite sign. In addition, the largely positive values for all constituents on the Pacific coast obtained by Jay (2009) can be clearly seen. In this region also, S_2 percentage changes are considerably larger than those for M_2. Positive trends for the diurnals can be observed on the Atlantic coast south of Cape Hatteras and in the Gulf of Mexico: further north a more mixed picture is obtained but the local sign of RPA tends to be supported by more than one record, which provides confidence in the quality of the data set and in the representativeness of the derived trends for the area. Occasionally, individual stations present values which do not conform to what appears to be the regional behaviour. For example, Ray (2009) discussed the consequences of tide gauge relocation at Bermuda, and the fact that the Wilmington record represents river rather than ocean tides, in his discussion of Atlantic S_2 change. Both of these examples can be seen as anomalies in Figure 4(a). Reasons for individual stations to depart from regional norms are discussed below. However, it can be seen that, if not too many stations have such problems, then it is still possible to arrive at regional conclusions.

RPL values (Figure 4b) are mostly negative for M_2, K_1 and O_1 (rather less so for S_2) for the Pacific coast with the exception of the area around and to the north of Vancouver. Positive and negative trends tend to exist in clusters on the east coast, especially so for the diurnals. Figure 4(c) presents values of PNOD obtained from the regression fits. On the Pacific coast, values are of the order of

0.5% or less at most locations, indicating that the equilibrium assumption employed in TASK was a good approximation for the real ocean. Non-equilibrium values exceed 1% at many locations on the Atlantic coast, especially so for the diurnals. However, given that the equilibrium nodal variations for diurnals are relatively large, a residual signal of only 1% still represents a fair representation of an equilibrium response. The non-zero percentage nodal values for S_2 on the Atlantic coast are a particularly interesting finding, given that S_2 is a solar constituent. NSIGN parameter values of -1 for almost all stations in this area indicate that maximum S_2 amplitude occurs when M_2 amplitude is minimum, consistent with non-linear shallow water interactions between the two main semi-diurnal constituents.

A more mixed picture is obtained in Europe than in N America. Figure 5(a) shows positive RPA for M_2, S_2 and O_1 in the eastern North Sea while the three constituents demonstrate both signs around the UK. K_1 trends are positive at most locations around the UK and in the region in general. Spatial consistency in RPL is harder to identify (Figure 5b). In the southern North Sea, many of the stations with positive RPA for M_2 tend to have negative RPL. S_2 RPL values are positive at most locations. RPL values for O_1 are positive on the east coast of the UK and on the adjacent European North Sea coast, but are negative on the west coast. A largely opposite pattern is seen for K_1. These findings can be considered in combination with those obtained by Shaw and Tsimplis (2009), who used records for more stations in the central and eastern Mediterranean than are in GESLA (most of their records had comparable length to those in subset B); negative trends in phase lag were obtained for most constituents.

Findings from the present analysis for the PNOD parameter (Figure 5c) show low values for M_2 in Scotland and of the order of 1% or less elsewhere around the UK, consistent with previous research (Woodworth et al., 1991). Larger values can be seen in the eastern North Sea and smaller ones on the Atlantic coasts of Norway and Iberia. For the majority of stations in this area NSIGN=-1. Larger values of PNOD for S_2 are obtained than for M_2 around the UK, and especially in the eastern North Sea, again with NSIGN=-1 and consistent with previous research (Amin, 1983, 1985). PNOD values for the diurnals are approximately 1% at most locations, suggesting a reasonable approximation of equilibrium expectations given the larger nodal variations for diurnals than for semi-diurnals.

For the Far East, Figure 6(a) shows most values for RPA for each constituent to be positive around Australia, with the main exception of several stations in South Australia for the semi-diurnals. Stations in Japan show mostly negative RPA values in the north and positive ones in the south. Positive values are obtained for the semi-diurnals at most tropical Pacific islands. RPL values are largely negative for all constituents around Australia and Japan (Figure 6b), although there is evidence for local clusters of opposite sign. Values of PNOD for the semi-diurnal constituents indicate greater spatial variability than for N America and Europe (Figure 6c). Exceptionally large values (~2%) are obtained for S_2 in SE Australia. PNOD values for K_1 and O_1 in Australia are larger in the east (~1%) than the west (~0.5%) while values of order 1% can be seen in Japan and at tropical islands.

Aside from the three regions discussed above, subset B contains only a small number of stations in S America and one station in Africa. The main conclusions from these regions are that RPA values for M_2 on the Pacific coast of S America are negative near to the Equator and positive further south (cf. Jay, 2009), while S_2 values are mostly positive. The diurnals show little spatial consistency. Values of RPL for M_2 are negative for most stations on the Pacific coast and positive in southern Brazil.

We now turn to the question of whether the trends in Figures 4-6 (a,b) (and similar figures with 5 times the colour scale range available in the PSMSL Author Archive) are significantly different from zero. This question can be addressed in several ways. First, the regression fits provide formal standard errors on the trends at each station, and findings at particular locations and for each constituent may be inspected in tables in the Author Archive. Second, a median standard error was calculated for each set of constituents derived from subset B stations. These values were 0.012, 0.017, 0.019 and 0.024 % per year and 0.012, 0.016, 0.013 and 0.015 degrees per year for M_2, S_2, K_1 and O_1 respectively with little evidence for a dependence of median error on record length (these values may be compared to standard errors of order 0.01 and 0.02 % per year obtained by Ray (2009) for M_2 and S_2 respectively using records of 70 years, see his Table 1). Third, the scatter of points in Figures 1 and 2 was inspected, giving standard deviations between subset A and B values of approximately 0.022 % per year and 0.030 degrees per year respectively, with similar values obtained for each constituent once outliers had been removed. These particular values could be said to represent overestimates of typical subset B errors as they will have been combined with uncertainties in the subset A trends. On the other hand, the median values could be claimed to be underestimates, as they are based on an ordinary least squares procedure which tends to underestimate formal standard errors.

Altogether, these calculations suggest that values of RPA greater than approximately 0.015 % per year in magnitude in Figures 4(a), 5(a) and 6(a) can be considered significantly different from zero, with perhaps a slightly higher threshold for the diurnal tides. In addition, a threshold of approximately 0.02 degrees per year would imply that only the RPL values for stations in Figures 4(b), 5(b) and 6(b) with saturated colour would be considered significant (additional figures with different colour scales are available in the Author Archive). In both cases, confidence in non-zero trends is increased where supporting evidence is available from nearby stations, a test which in general tends to support significant conclusions on changes in RPA rather than RPL.

4. Discussion and Conclusions

The real ocean tide can change for one or more reasons including:

1. Long term changes in the tidal potential (Cartwright and Tayler, 1971; Cartwright and Edden, 1973). Such changes are small on century timescales and can be disregarded for present purposes
2. Interactions between the tide and the continuum of non-tidal sea level variations (Munk and Cartwright, 1966). Such interactions manifest themselves as changes in tidal constants from year to year, and they could result in a long term trend in tidal parameters if a corresponding component exists in the non-tidal forcing.
3. Changes in water depth, due to sea level rise or geological processes such as Glacial Isostatic Adjustment, resulting in modifications in tidal wavelengths. However, large

changes in water depth are usually required to change tidal constituents significantly (e.g. Flather et al., 2001).

4. Morphological changes in coastal waters, harbours or estuaries, either natural (e.g. Araújo et al., 2008) or anthropogenic (e.g. dredging) in origin, resulting in modifications of local tides.
5. Changes in the internal tide with corresponding small changes in its surface expression (e.g. Ray and Mitchum, 1997; Mitchum and Chiswell, 2000; Colosi and Munk, 2006). Such changes can occur even though the barotropic tide is invariant.

In addition, the tide can appear to have changed for a number of technical reasons. Examples include:

6. Undocumented change of tide gauge location within a large estuary or harbour.
7. Change in tide gauge technology. Many tide gauge authorities have changed technology in recent years from conventional float and stilling well gauges to either pressure, acoustic or radar-based systems (IOC, 2006).
8. Timing or calibration errors or other data irregularities.

Within any regional tidal survey, it should be possible to detect those changes which result from factors 4, 6 and 8, as they will be anomalous in either a spatial distribution of tidal parameters (factor 4) or as outliers in time series of tidal constants (factors 6,8). Factor 5 will also not be coherent over large regions but should not result in trends without large changes in ocean density profiles.

Systematic changes in tidal information due to factor 7 are potentially a very important consideration, as most tide gauge authorities have changed their recording technology during the last few decades and few agencies have undertaken as rigorous a comparison of data acquired during periods of technology transition as one would like. Technology biases are more likely in RPA than in the other parameters, but could also occur in RPL, especially when float gauges are replaced by other techniques, due to the removal of the lags inherent in stilling wells. RPA changes will result from calibration errors in one or more of the technologies. These could include uncompensated temperature-dependent biases which tend to be diurnal and seasonal in nature, although effects in other harmonics cannot be excluded. Errors in RPA obtained from pressure-based tide gauges can result from imprecise density correction; at many locations an average density will have been employed, while the real water density may have been both tidally and seasonally dependent.

Systematic changes due to factor 7 might be identifiable by comparison of data from different authorities in the same country, as each authority is unlikely to have changed technology at the same time, and by comparison of information between neighbouring countries. It can be seen that regional consistency is again the most important criterion at our disposal for detecting errors in individual records.

Although it is important to always keep concerns about data quality in mind (factors 6-8), the tidal survey presented above has shown that is possible to make use of the currently available data set to investigate the extent to which ocean tide parameters are changing on a regional basis. It can be seen that, where more than one record is available from a region (even one as small as the southern North Sea), then one tends to obtain spatial consistency in findings. Therefore, it seems that records of length 30 years or more can be used to infer century-timescale change in regional tidal amplitudes and phase lags. In addition, they can provide interesting information on the nodal dependence of the tide, consistent with that obtained from longer records. Our insight into such changes will grow as the GESLA data set is extended to include records from other countries. Our main findings so far indicate that there is little evidence in Europe or the Far East for the extensive changes to the main tidal constituents observed previously in N America. Nevertheless, evidence for regional and local changes can be clearly seen where the density of information allows, and outliers can usually be spotted. It seems, therefore, that tidal changes may be commonplace around the world, although not necessarily the same in character between regions.

An important additional finding relates to the extent to which the temporal variation of each constituent departs from equilibrium expectations in different parts of the world. In particular, sizeable ‘nodal’ signals are obtained for S_2 at many locations, suggestive of interaction between constituents (and much larger than a negligibly small nodal variation of 0.22% of the S_2 amplitude due to a luni-solar interaction component in the astronomical tidal potential, Cartwright and Tayler, 1971). In our experience, such a possible nodal dependence of S_2 is seldom included in tidal analysis and prediction software packages (and probably should not be until its origin is better understood).

The study of the ocean tide has a long history (Cartwright, 1999). Its main components are now known to centimetre accuracy (e.g. Shum et al., 1997). However, there are still many aspects of tides which remain to be studied and their temporal variability represents one important area. For example, the fact that tidal constants vary seasonally has been known for many years but the reasons for such variations, which occur especially in shallow waters (e.g. Pugh and Vassie, 1992; Kang et al., 2002) and at high latitudes (e.g. Prinsenberg, 1988; Kagan and Sofina, 2009), remain poorly understood. In addition, there are interannual changes due to interactions with meteorologically-forced sea level variations (e.g. Munk et al., 1965; Bernier and Thompson, 2007) and conceivably with interannual and decadal changes in ocean circulation and stratification near topography (e.g. Jay, 2009) which require further study. Consequently, the long term tidal changes discussed in the present paper can be seen to occupy the low-frequency end of research into tidal variability. Long term changes in the tide at particular locations have been noted a number of times before (e.g. Cartwright 1971, 1972; Godin, 1995; Pouvreau, 2008). However, it has not been until recently that more comprehensive regional studies have been undertaken, with quite intriguing findings. One important example has been the identification of the variation in S_2 in NE America. As discussed by Ray (2009), these observed changes are undoubtedly real, but they are much larger than can be explained in terms of changes in the astronomical tidal potential (factor (1) above), and an explanation in terms of a proportionately larger change in S_2's radiational component is not as yet conclusive.

In the course of constructing the present paper, I learned of a similar global tidal study by Müller et al. (2010). That work concentrates on 50 long (typically more than 60 years) records obtained from the same UHSLC and GLOSS data banks as the present work, and performs a set of sensitivity studies in order to understand why tides may have changed. There are many similarities in the findings of the two studies, in spite of the Müller et al. focus on longer records and the present work's attempts to use more of the shorter ones. There are also some differences that are probably related to record length. While each study has its own emphasis, they together demonstrate the widespread character of tidal change during the 20th and early 21st centuries.

These tidal changes demand further investigation by continued analysis of historical data sets and by numerical modelling. Some of them, especially the larger-scale ones, may prove to be of major geophysical significance and are, therefore, worthy of study in their own right. However, even the regional and local ones need to be understood as far as possible, if the insights obtained are to be incorporated into the tidal prediction schemes and tidal models needed for many practical purposes. Tidal predictions are used routinely for flood warning and navigation and by many users of coastal waters, and in some applications the highest accuracy of prediction is not required. However, there are many other applications where the most accurate tidal information is a necessity, such as in the computation of extreme levels for coastal engineering. Another application which has recently become apparent is in the optimal exploitation of satellite radar altimetry in shelf seas (Cippolini et al., 2009; Ray et al., 2010). Tidal prediction schemes and tidal models that can represent the long term tidal variability discussed above are certain to find application in the coastal and oceanographic communities.

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Ancillary Material

The PSMSL Author Archive (www.psmsl.org/products/author_archive) contains additional maps and ancillary material. A readme file describes the contents of each directory.

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Table 1

Correlations between values for each tidal parameter using either subset A or subset B data selection criteria for those station records long enough to be selected in subset A. Numbers in brackets indicate the number of subset-pairs in each case.

	RPA	RPL	PNOD
M_2	0.823 (52)	0.756 (51)	0.920 (52)
S_2	0.948 (48)	0.780 (46)	0.821 (48)
K_1	0.838 (54)	0.740 (53)	0.958 (54)
O_1	0.832 (53)	0.751 (51)	0.919 (53)

Table 2

Number of occasions on which the same or different value of NSIGN was obtained using the two data selection criteria as in Table 1 and, for those stations with the same value of NSIGN, whether that value was +1 or -1.

	Same NSIGN	Different NSIGN	NSIGN = +1	NSIGN = -1
M_2	46	6	17	29
S_2	42	6	6	36
K_1	46	8	18	28
O_1	48	5	24	24

Figure Captions

1. Values of RPA obtained using subset A (abscissa) and subset B (ordinate) selection criteria for M_2, S_2, K_1 and O_1. The dotted line corresponds to equal values.

2. Values of RPL obtained from subset A (abscissa) and subset B (ordinate) selection criteria. The dotted line corresponds to equal values.

3. Values of PNOD obtained from subset A (abscissa) and subset B (ordinate) selection criteria. The dotted line corresponds to equal values.

4. (a-c) Values of RPA, RPL and PNOD respectively for M_2, S_2, K_1 and O_1 for stations in subset B in North America. Stations marked by a small black dot do not satisfy one or both of the requirements described in the text.

5. (a-c) As Figure 4 for stations in Europe.

6. (a-c) As Figure 4 for stations in the Far East.

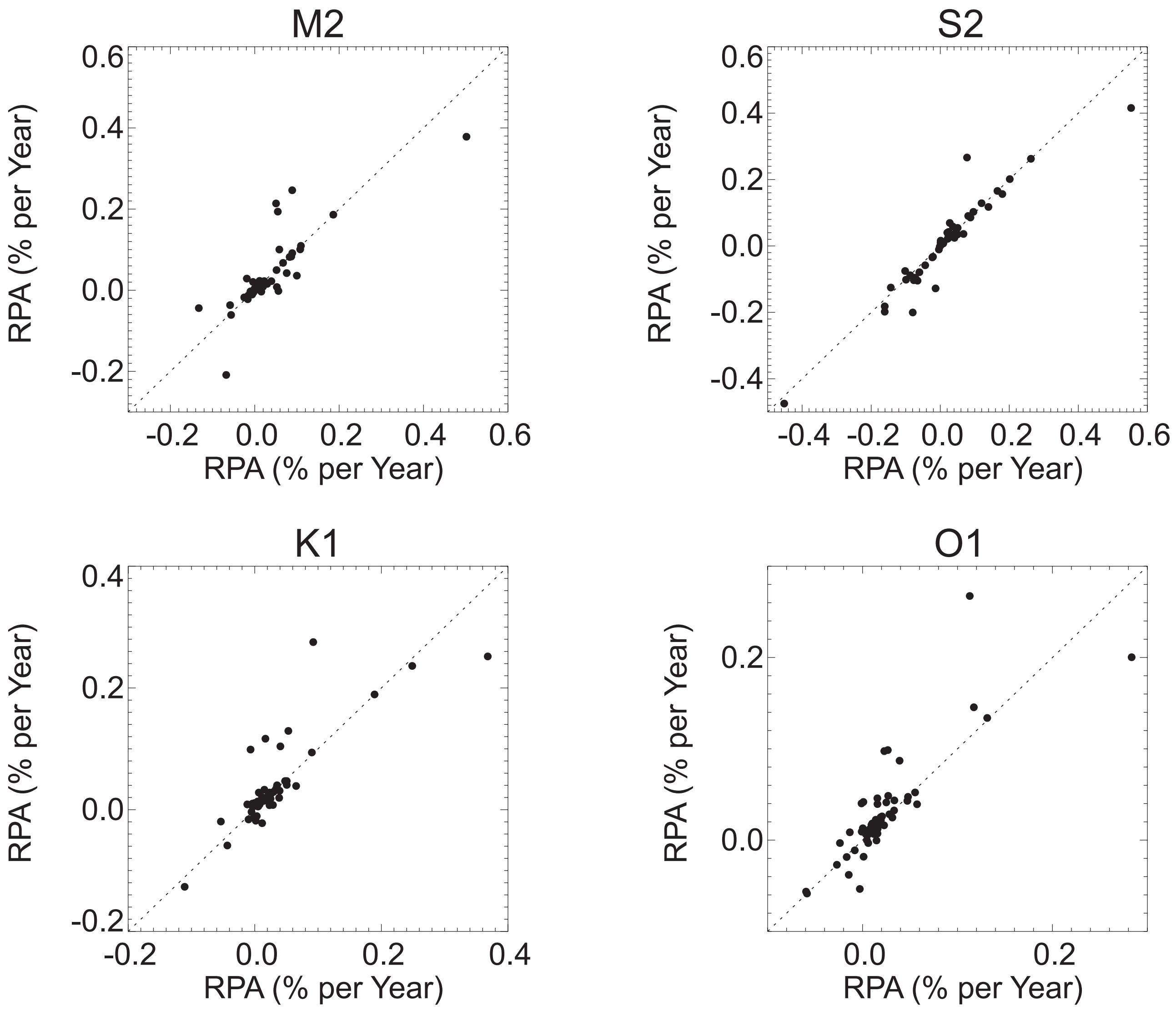

M2
S2
K1
O1
RPA (% per Year)
0.6
0.4
0.2
0.0
-0.2
-0.4
RPA (% per Year)
-0.4 -0.2 0.0 0.2 0.4 0.6
-0.2 0.0 0.2 0.4

Figure 1

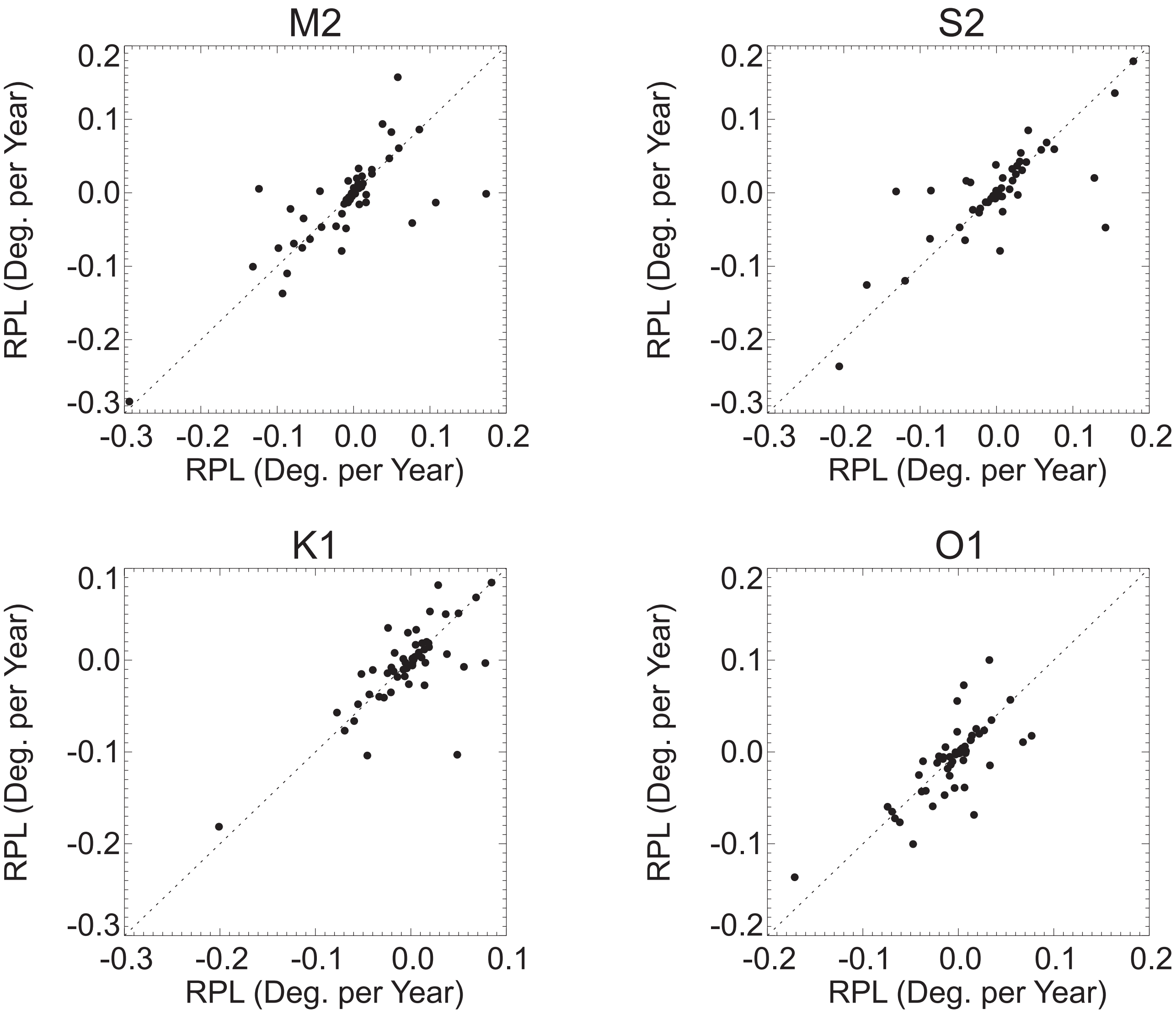

M2
S2
K1
O1
RPL (Deg. per Year)
RPL (Deg. per Year)
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.3
-0.2
-0.1
0.0
0.1
0.2

Figure 2

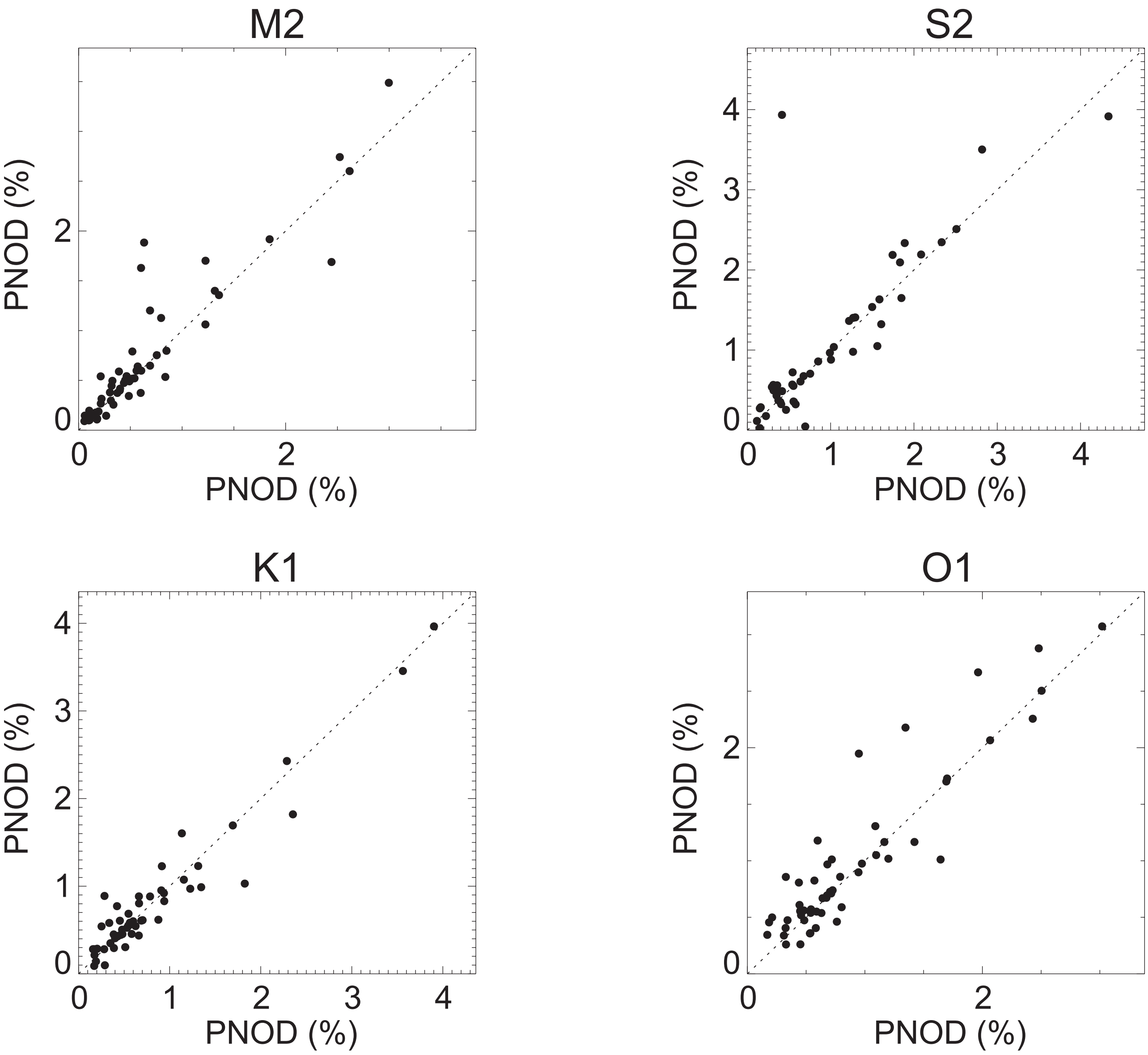
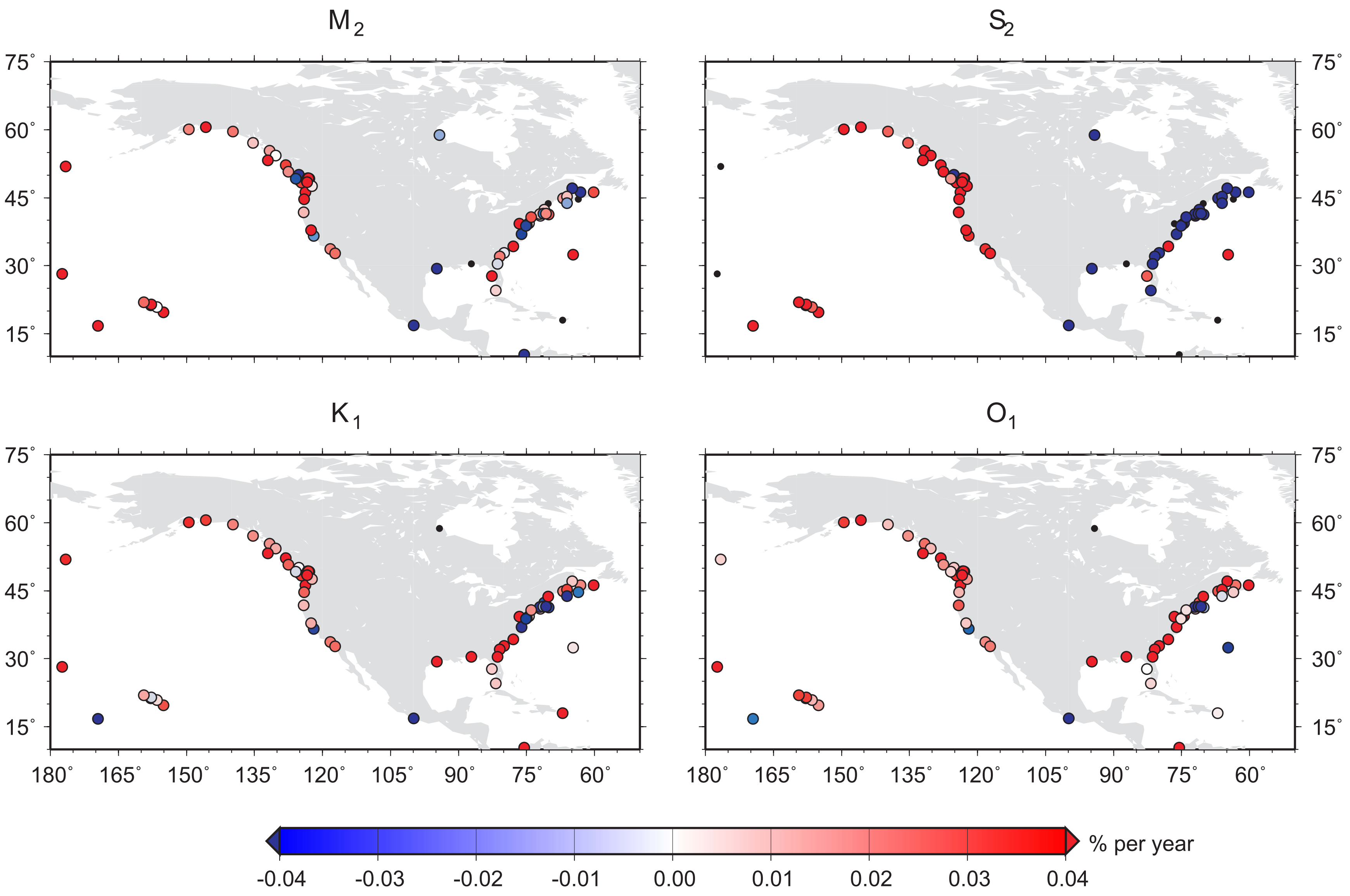
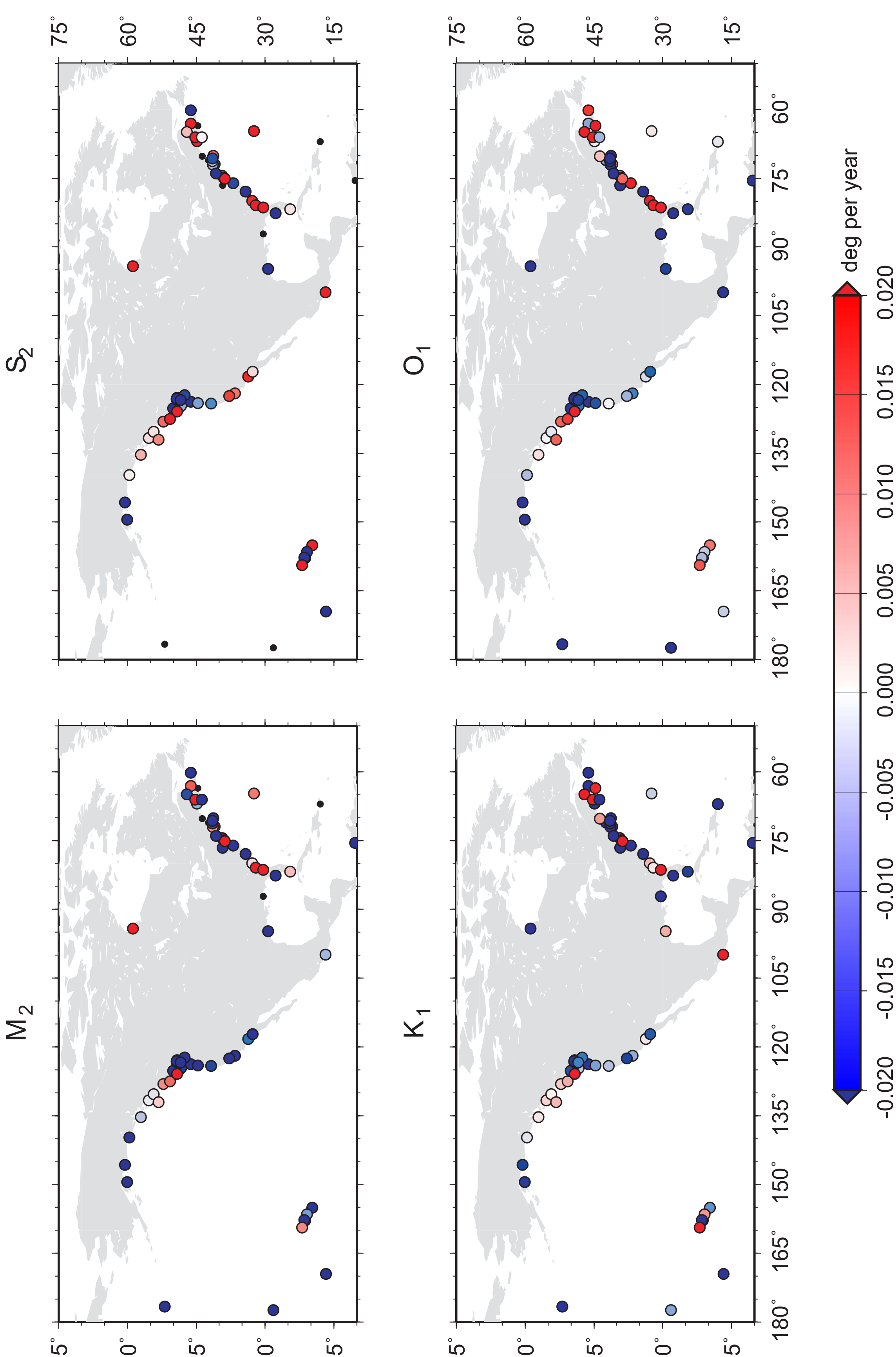


Figure 3

Figure 4 a,b,c follows


M2
S2
K1
O1
75°
60°
45°
30°
15°
180°
165°
150°
135°
120°
105°
90°
75°
60°
-0.04
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
% per year


M2
S2
K1
O1
75°
60°
45°
30°
15°
180°
165°
150°
135°
120°
105°
90°
75°
60°
-0.020
-0.015
-0.010
-0.005
0.000
0.005
0.010
0.015
0.020
deg per year

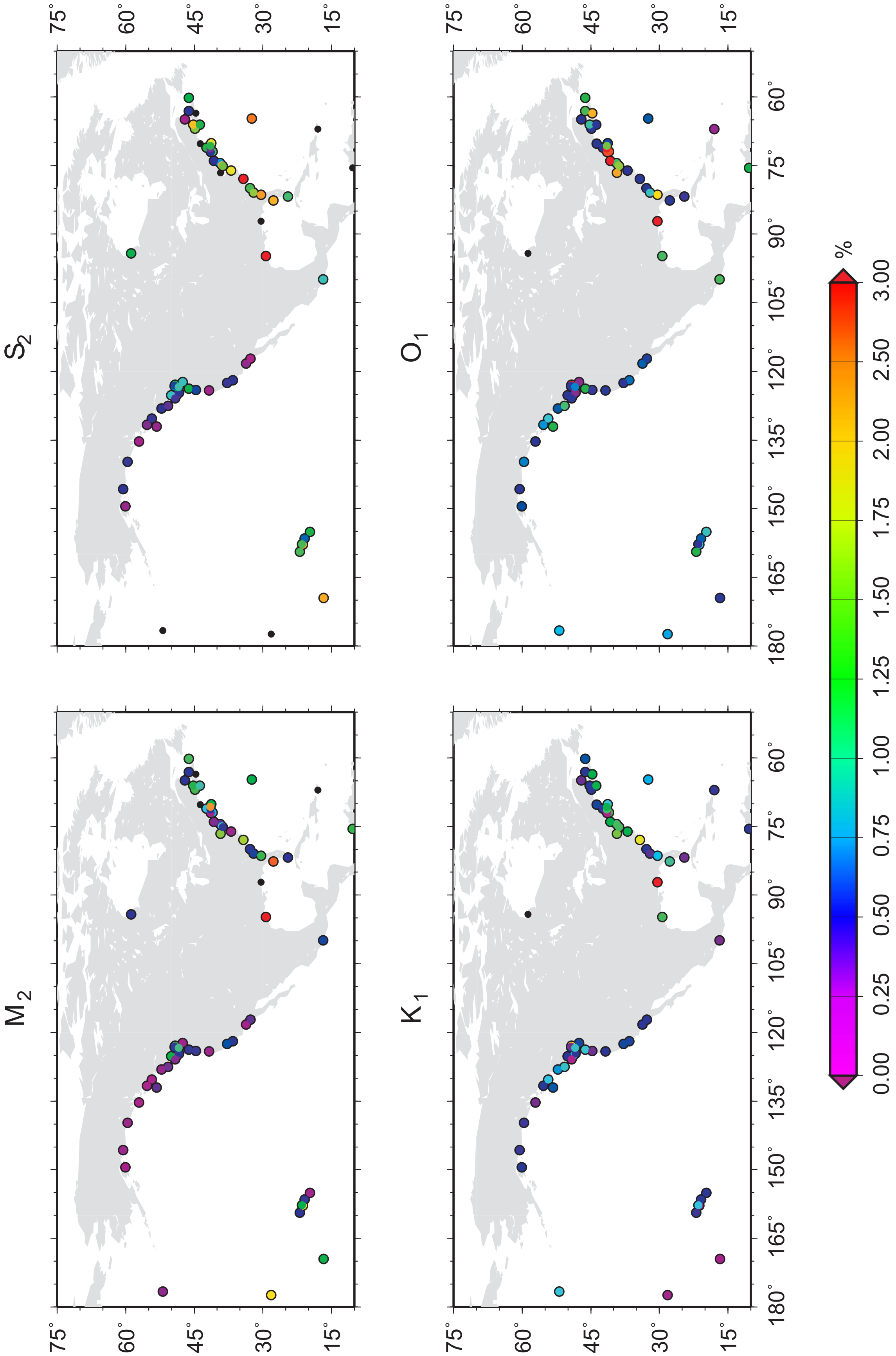
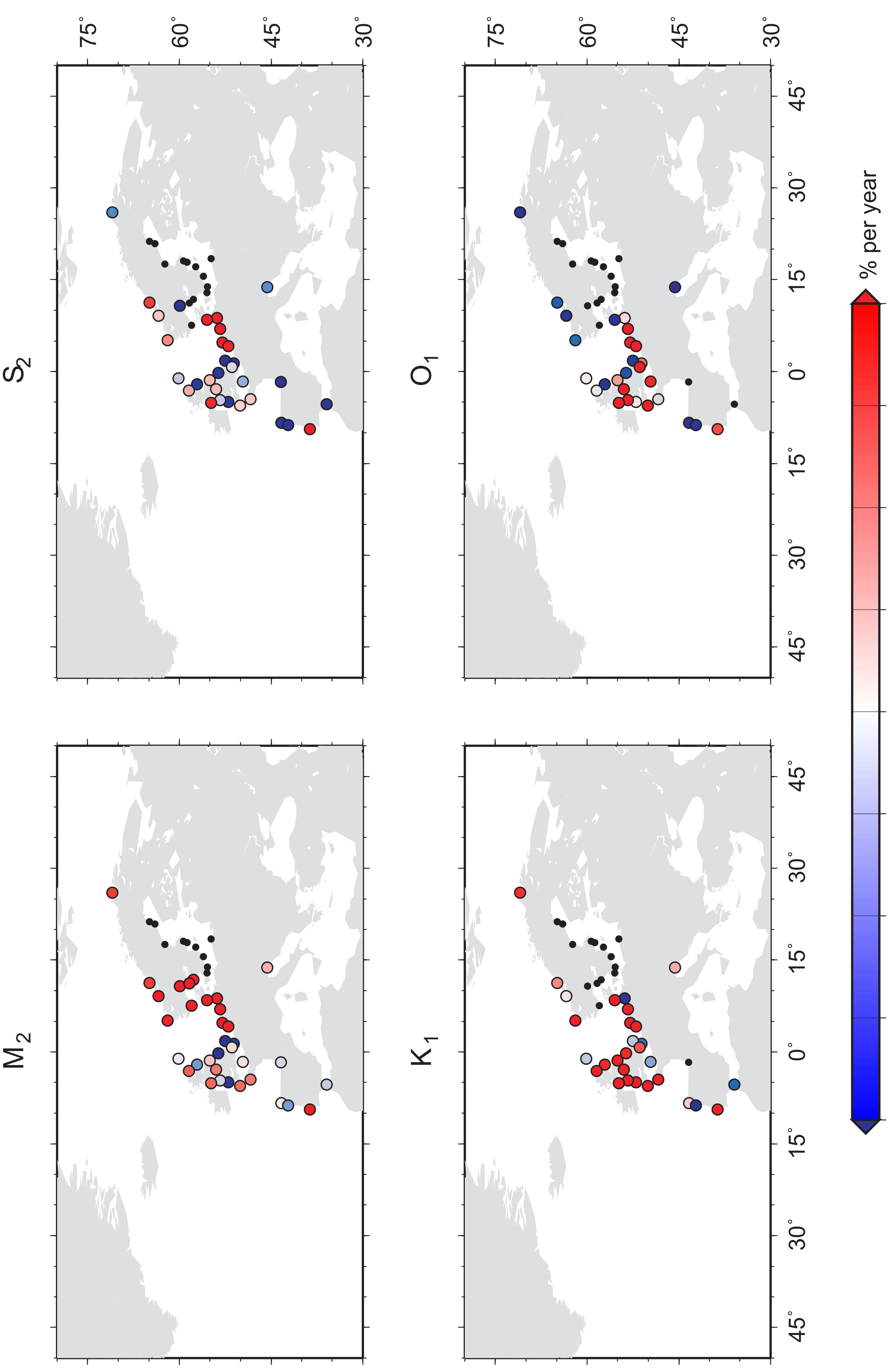
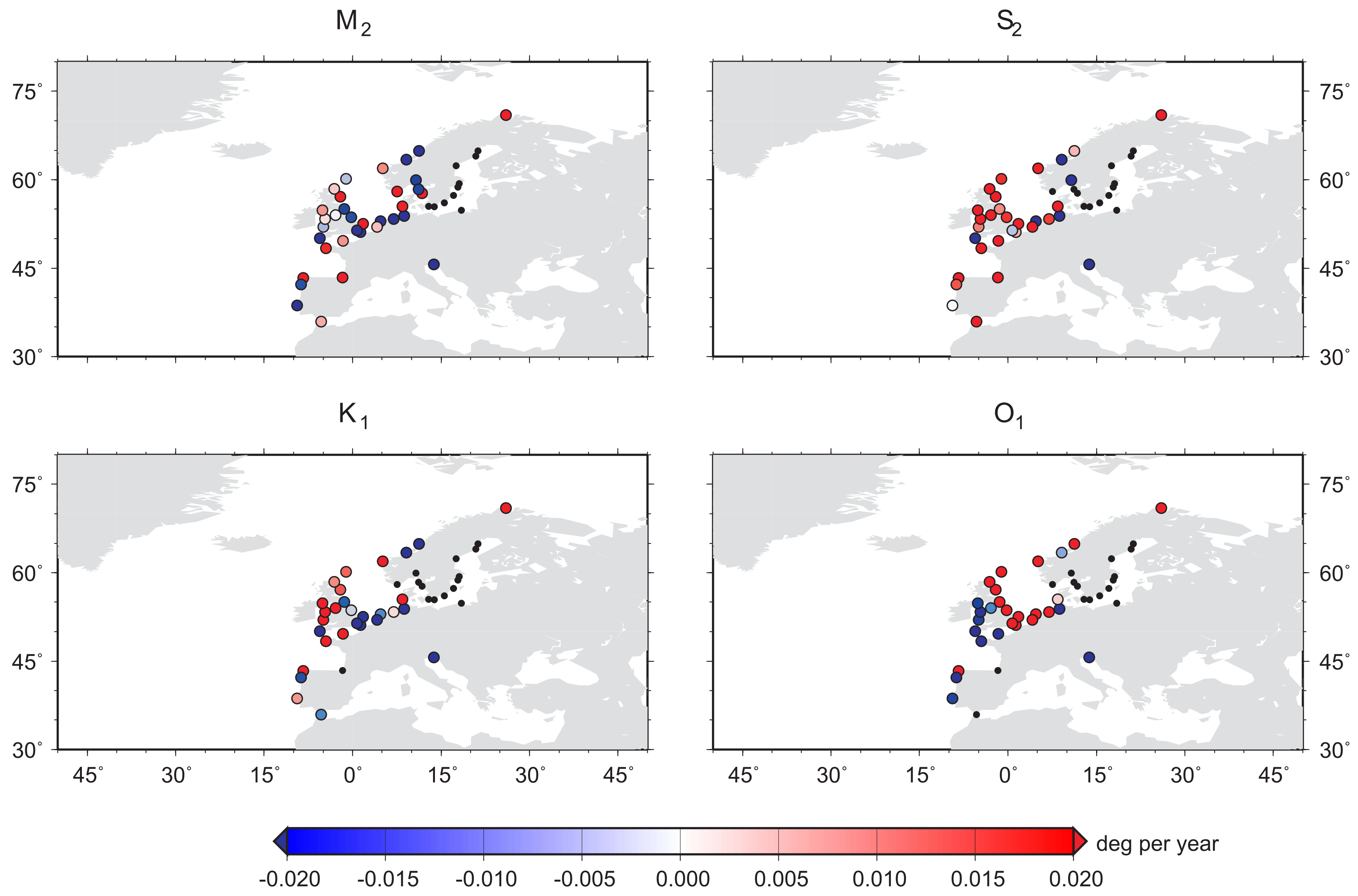

M$_2$
S$_2$
K$_1$
O$_1$
75°
60°
45°
30°
15°
180°
165°
150°
135°
120°
105°
90°
75°
60°
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.50
3.00
%

Figure 5a,b,c follows



M$_2$
S$_2$
K$_1$
O$_1$
75°
60°
45°
30°
45°
30°
15°
0°
15°
30°
45°
-0.04
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
% per year


M$_2$
S$_2$
K$_1$
O$_1$
75°
60°
45°
30°
45°
30°
15°
0°
15°
30°
45°
-0.020
-0.015
-0.010
-0.005
0.000
0.005
0.010
0.015
0.020
deg per year

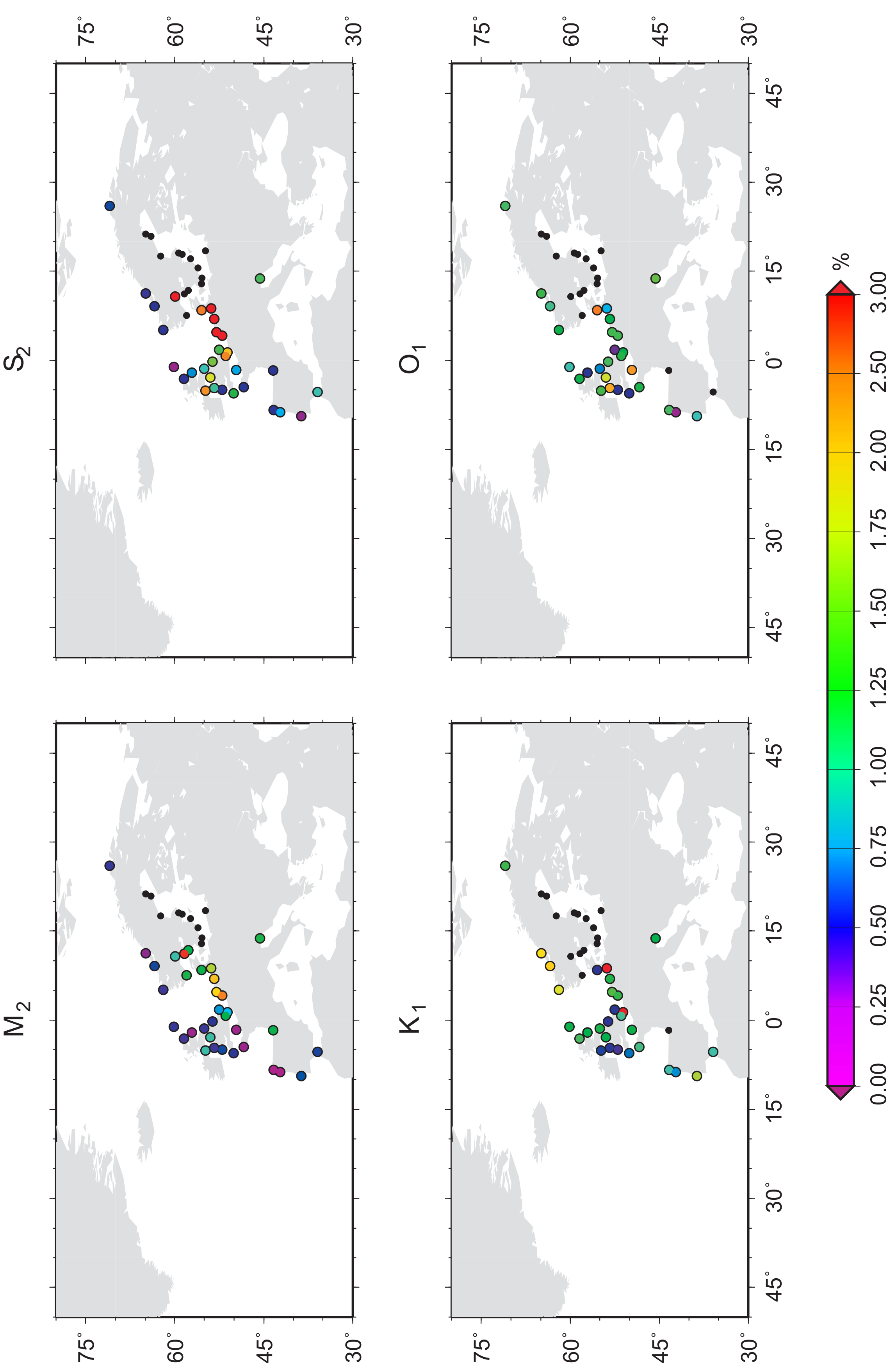
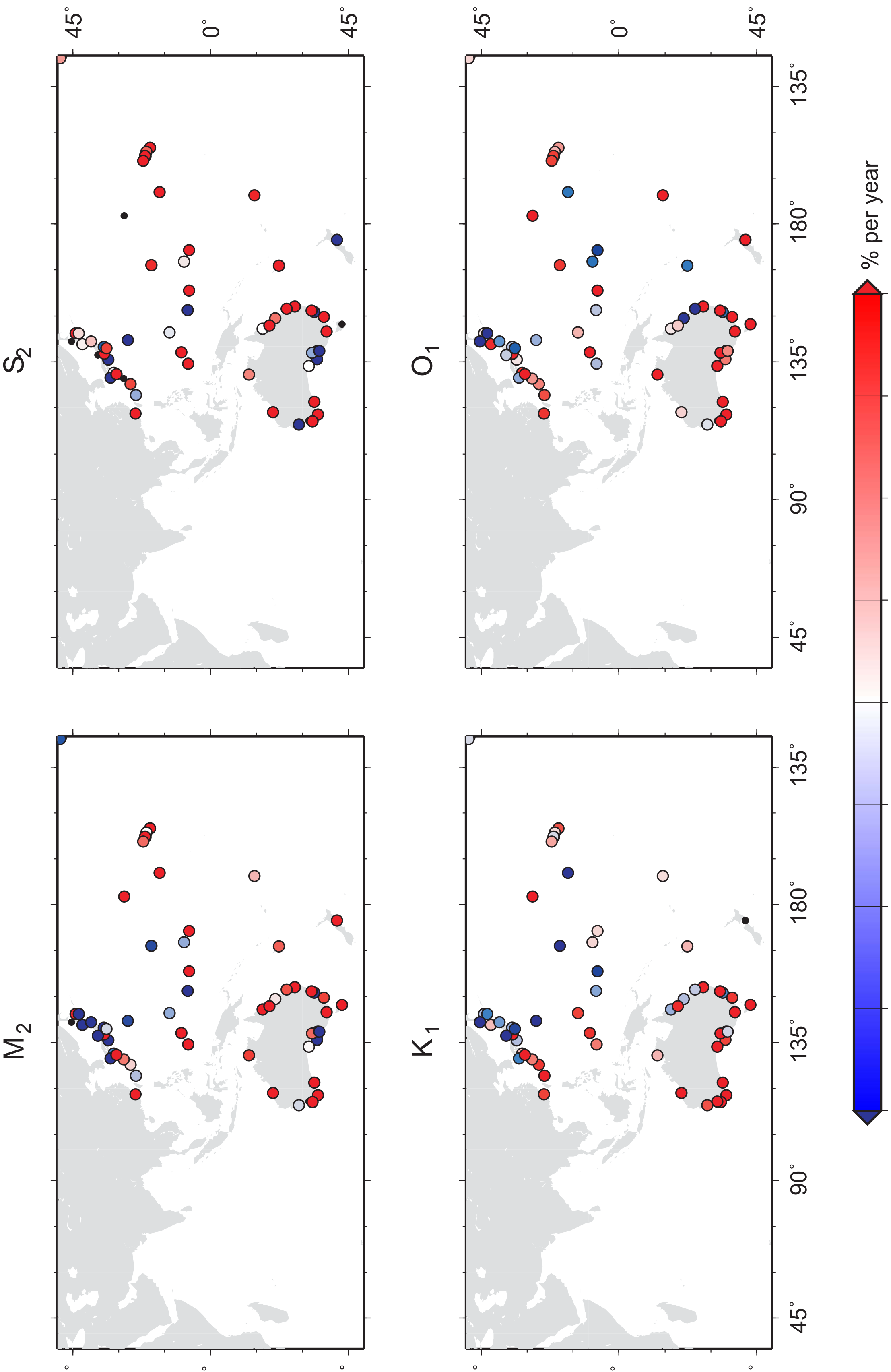
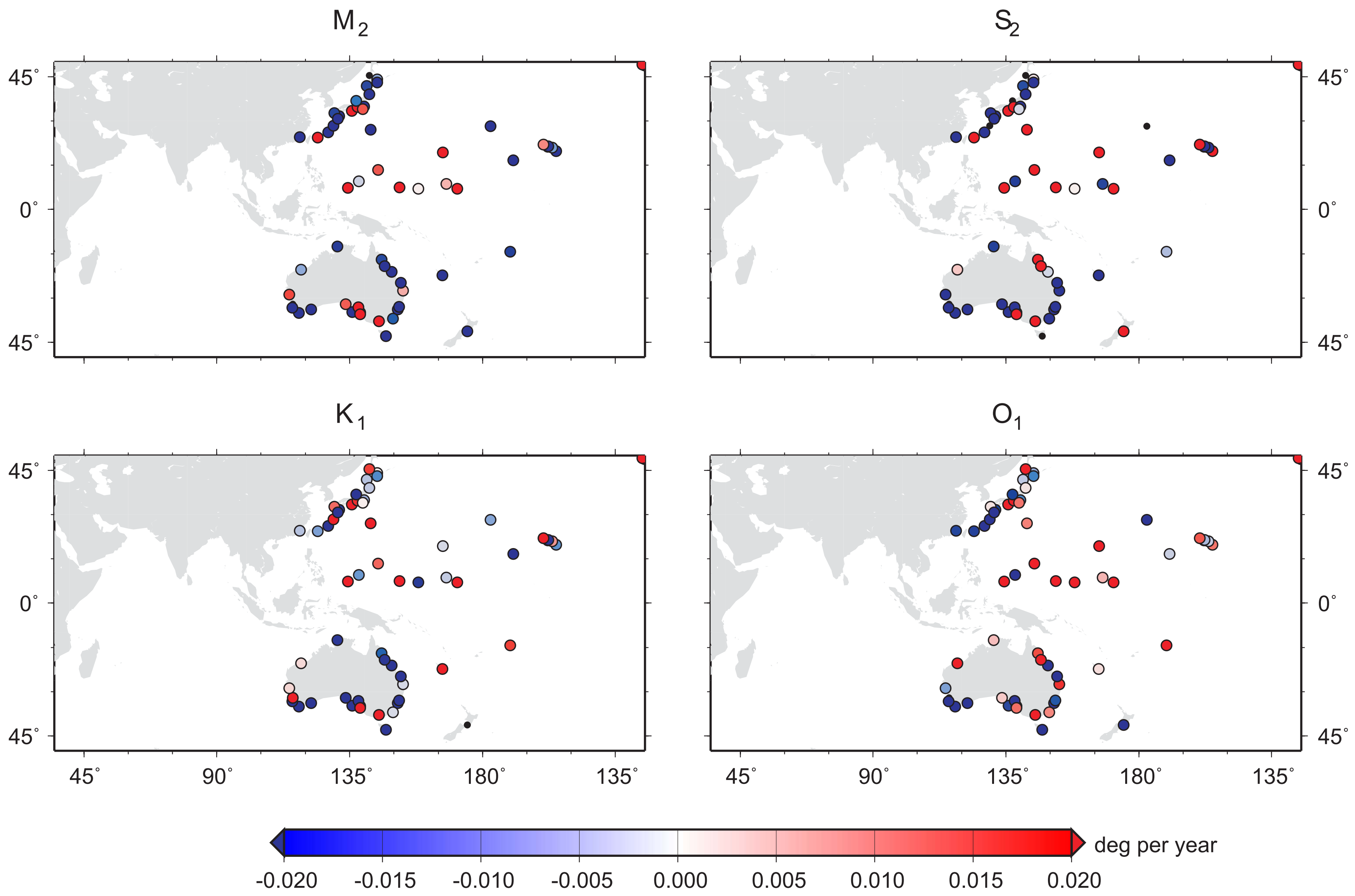
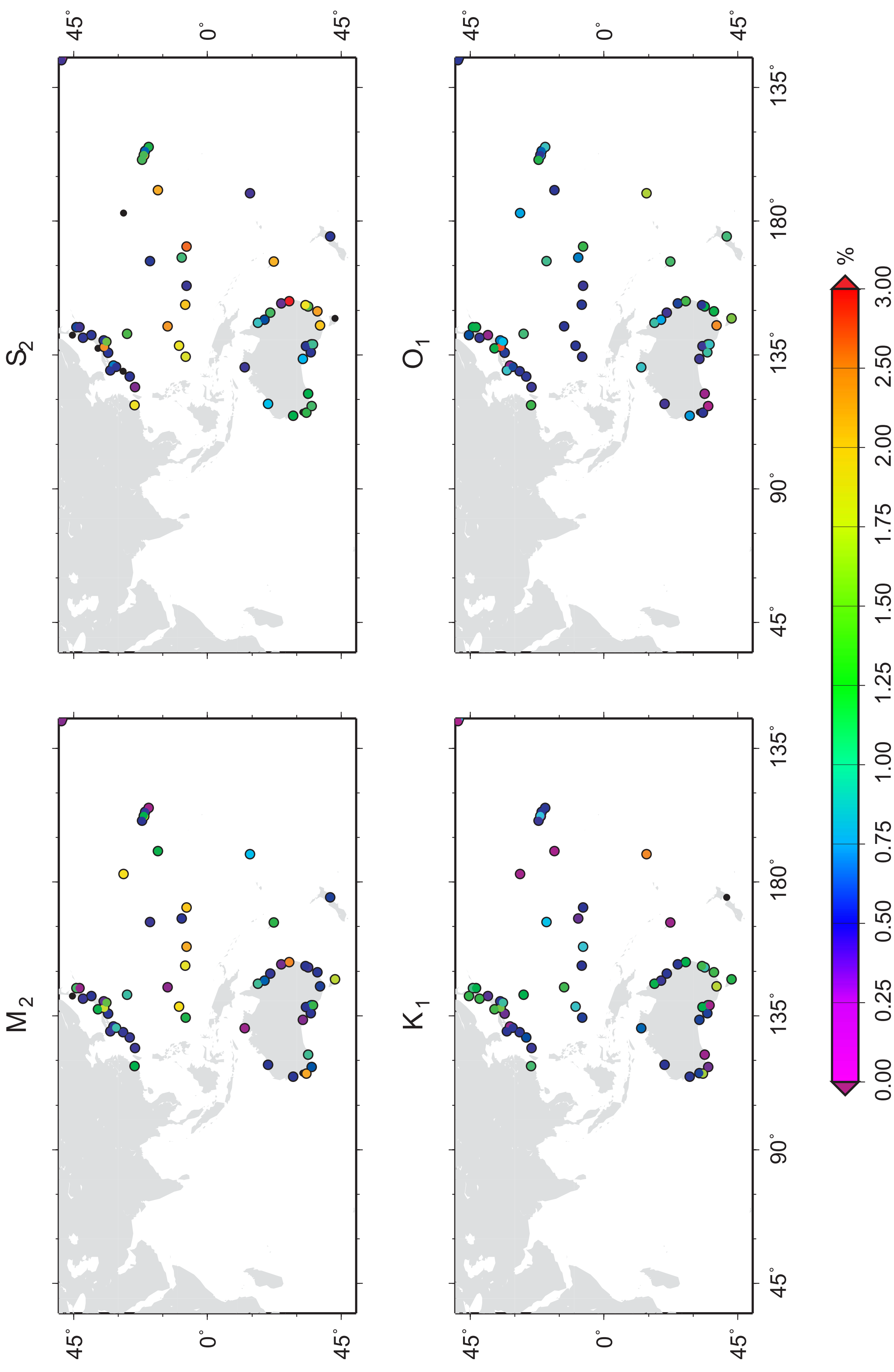
M$_2$
S$_2$
K$_1$
O$_1$
75°
60°
45°
30°
45°
30°
15°
0°
15°
30°
45°
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.50
3.00
%

Figure 6a,b,c follows


M$_2$
S$_2$
K$_1$
O$_1$
45°
0°
45°
45°
90°
135°
180°
135°
-0.04
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
% per year


M_2
S_2
K_1
O_1
45˚
0˚
45˚
45˚
90˚
135˚
180˚
135˚
-0.020
-0.015
-0.010
-0.005
0.000
0.005
0.010
0.015
0.020
deg per year


M$_2$
S$_2$
K$_1$
O$_1$
45°
0°
45°
45°
90°
135°
180°
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.50
3.00
%