Elsevier Editorial System(tm) for Advances in Space Research
Manuscript Draft

Manuscript Number: ASR-D-12-00114R1

Title: Seasonally steady planetary disturbances in the troposphere and stratosphere as seen in 30 years of NCEP reanalysis data

Article Type: ES

Keywords: reanalysis; planetary scale disturbances

Corresponding Author: Dr Peter Alexander, Ph.D.

Corresponding Author's Institution: Universidad de Buenos Aires

First Author: Peter Alexander, Ph.D.

Order of Authors: Peter Alexander, Ph.D.; Mario Rossi

Abstract: Zonal velocity and temperature daily global reanalysis data of 30 years are used to search seasonally steady planetary disturbances in the middle troposphere (400 hPa) and middle stratosphere (10 hPa). Significant wavenumber 1, 2 and 3 modes are found. Constant phase lines of zonal velocity 1 modes exhibit significant inclination angles with respect to the meridians. The winter hemisphere generally shows a more significant presence of structures. The Northern Hemisphere (NH) exhibits all over the year a larger amount of structures and more intense amplitudes than the Southern Hemisphere (SH). Middle latitudes exhibit the most significant cases and low latitudes the least significant ones. Longitudinally oriented land-sea transitions at +- 65 deg and -35 deg latitudes appear to play a significant role for the presence of steady planetary modes. The stratosphere exhibits a much simpler picture than the troposphere. Large scale structures with respectively NE-SW (NH) and NW-SE (SH) tilts in the observed temperature and zonal velocity constant phase lines recall the quasi-stationary Rossby wave trains that favor the poleward transport of angular momentum.

Highlights

-Steady planetary disturbances show significant wavenumber 1, 2 and 3 modes.
-Middle and low latitudes exhibit respectively the most and least significant steady structures.
-Longitudinally oriented land-sea transitions at + - 65 deg and - 35 deg latitudes appear to play a significant role for the presence of steady planetary modes.
-The stratosphere exhibits a much simpler picture than the troposphere.

Seasonally steady planetary disturbances in the troposphere and stratosphere as seen in 30 years of NCEP reanalysis data

P. Alexander

Departamento de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, 1428 Buenos Aires, Argentina, Telephone 54-11-4576-3353, Fax 54-11-4576-3357

M. Rossi

Departamento de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, 1428 Buenos Aires, Argentina, mprossi007@gmail.com

Abstract

Zonal velocity and temperature daily global reanalysis data of 30 years are used to search seasonally steady planetary disturbances in the middle troposphere (400 hPa) and middle stratosphere (10 hPa). Significant wavenumber 1, 2 and 3 modes are found. Constant phase lines of zonal velocity 1 modes exhibit significant inclination angles with respect to the meridians. The winter hemisphere generally shows a more significant presence of structures. The Northern Hemisphere (NH) exhibits all over the year a larger amount of structures and more intense amplitudes than the Southern Hemisphere (SH). Middle latitudes exhibit the most significant cases and low latitudes the least significant ones. Longitudinally oriented land-sea transitions at ± 65^o and -35^o latitudes appear to play a significant role for the presence of steady planetary modes. The stratosphere exhibits a much simpler picture than the troposphere. Large scale structures with respectively NE-SW (NH) and NW-SE (SH) tilts in the observed temperature and zonal velocity constant phase lines recall the quasi-stationary Rossby wave trains that favor the poleward transport of angular momentum.

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Email address: `peter@df.uba.ar` (P. Alexander)

1. Introduction

A large fraction of the spatial variability of the atmosphere is produced by modes of global scales and temporal intervals on the order of seasons. They are mainly forced by airflow over topography and large-scale thermal factors. Lau (1979) indicated that this quasi-steady component plays a dominant role in the local balances of momentum and energy, whereas the transient contributions have a secondary importance. This showed that a better knowledge of these nearly stationary structures was very relevant to an adequate description of the general circulation.

Planetary scale disturbances like Kelvin and Rossby waves have a significant role in the winter or spring stratosphere, but they are also important in the troposphere in relation to meteorological phenomena (see e.g. Hansen and Sutera, 1986). Stationary planetary waves largely contribute to the middle and upper atmosphere dynamics and are related to the sudden stratospheric warmings. There is a strong seasonal variation of stationary planetary waves in the stratosphere (see e.g. Randel, 1988). Charney and Eliassen (1949) and Smagorinsky (1953) in the troposphere and Charney and Drazin (1961), Matsuno (1970) and Schoeberl and Geller (1977) in the stratosphere were probably among the first ones to develop a framework trying to explain some of the features of planetary waves. Diverse observational works contributed later on to the description of these waves (Hartmann, 1977; Smith, 1983; Barnett and Labitzke, 1990; Li et al, 2006; Shepherd and Tsuda, 2008; Xiao et al, 2009; Mukhtarov et al, 2010). However, many aspects of the planetary disturbances are presently not completely understood, so further studies of them should be performed. As a large fraction of planetary disturbances generated in the troposphere propagate into the stratosphere, knowledge of their presence and seasonal evolution throughout both layers may be important. Analyzes in both hemispheres may yield clarifications because forcing mechanisms and climatologies are different in both areas. Notable differences in the features between the two geographical halves have become apparent (see e.g. Hio and Hirota, 2002): in the Northern Hemisphere (NH), the forcing during winter of stratospheric stationary planetary waves is considered to be due mainly to the large-scale topography, whereas in the Southern Hemisphere (SH) stratosphere forcing from the Indian Ocean region as well as orographic and thermal forcing from the Antarctic continent have been suggested. The surface topographies are also quite different in the two hemispheres. All these studies may provide validations for numerical global model solutions. The present study takes advantage of a long dataset, which provides robust estimates of seasonal characteristics of stationary planetary structures in the troposphere and stratosphere all over the globe.

2. Data

Apparent climate changes resulted from modifications introduced in the operational global data assimilation system to improve forecasts about 20 years ago. This motivated the National Centers for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) reanalysis project. The basic idea is to use a frozen state-of-the-art analysis/forecast system and perform data assimilation using information from the past up to the present to produce a retroactive record of more than 50 years of atmospheric fields (Kistler et al., 2001). Data from rawinsondes, balloons, aircraft, ships, surface stations, and satellites are first scrutinized through a quality check, then they are fed into the assimilation model that includes parameterizations for all major physical processes, and finally they become analyzed again for self-consistency. All data are given on a 144 x 73 global grid at constant pressure levels. The NCEP reanalyses now cover the years from 1948 to the present. In 1979 the satellite-observing system was established, which partially affected reanalysis results. For example, some phenomena as depicted in the NCEP reanalysis data exhibit a discontinuous behavior around 1978 in diverse variables (Huesmann and Hitchman, 2001, 2003; Kistler et al., 2001). The emergence of satellite data resulted in a significant change, indicating that the results from 1979 to present day are the most reliable and coherent ones. The global features before that year are rather governed by the model outcome in data-sparse areas, leading to the possible generation of some spurious results in those regions.

Different outputs of the reanalyses are not equally reliable. The NCEP/NCAR fields have been graded according to the relative influence of the observed data and the assimilation model on the output field. Atmospheric temperature (T) and zonal wind (U) are significantly affected by the observations, and the numerical model does not have a strong influence. Therefore they are among the variables with the highest grade, which are considered to provide an estimate of the state of the atmosphere better than would be obtained just with measurements. In this work we analyzed global zonal oscillations of seasonal means of daily air temperature and zonal wind reanalysis data over 30 years (1979-2008). We grouped data into seasons DJF (December, January, February), MAM (March, April, May), JJA (June, July, August), SON (September, October, November). We have chosen levels in the middle troposphere at 400 hPa and in the middle stratosphere at 10 hPa. We performed Fourier analysis on the 144 data at each of the 73 latitudes. Zonal averages were initially removed in each dataset. In order to keep the most relevant fluctuations of the analysis, the following procedure was followed in each dataset. Typical planetary waves exhibit an amplitude of 1 K in temperature and 2 m/s in zonal velocity (Andrews et al, 1987; Mohanakumar, 2008). We used these values as the lower limits in order to keep the modes coming out from the Fourier analysis. We set a priori no upper constraint on the wavenumber w representing planetary scales and the shortest mode that emerged from all our analyzes with a relevant structure (amplitude above the lower limits) was $w = 3$.

3. Results

Significant features that differ from the well-known behavior of a wave have been found below in several cases and therefore these patterns are called here structures. For example significant perturbations in one variable have not been always accompanied by the other variable or clear phase differences between them (polarization relations) did not clearly come out. However, we cannot discard that the wave relations are present, but are small or obscure enough to avoid detection. The amplitude limit selection criterium outlined above was partially arbitrary (but necessary) and therefore the latitude ranges of modes exhibited below should be considered of an indicative rather than of an accurate nature. In particular, temperature and zonal wind oscillations exhibit similar features at some given altitudes and seasons but the latitude bands of occurrence exhibit moderate differences among them in some cases. In order to represent the detected structures we used amplitude and phase from the Fourier analysis to plot the location of maxima and minima of modes $w = 1$, 2 and 3 on topographic maps.

Regarding the use of any possible spectral representation tool of quasiperiodic structures, every particular choice gives more visibility to certain patterns of the data and obscures other characteristics. The way information is processed ultimately affects the results and their corresponding interpretations. Applying a Fourier decomposition to given atmospheric data and interpreting the components as waves implies that we assume that nature has building blocks with a certain shape. In addition, we should check if observations reproduce the physical laws or equations of waves or their consequences (conservation of given quantities, polarization relations between certain variables, spectral shapes, etc).

3.1. The troposphere

In Figure 1 DJF shows a rich deployment of structures in the NH for $w = 1$, 2 and 3, with the strongest values at middle latitudes. The SH exhibits a more limited activity at high and middle latitudes. The Antarctica land-sea interface at about -65^o latitude produces changes in the observable patterns. A similar behavior (mainly in zonal wind U the features disappear northwards) is observed close to the latitude of the Southern border of Africa and Australia, at about

-35^o. Figure 2 shows that in MAM there are structures in the NH for $w = 1$, 2 and 3, with the strongest values at middle latitudes. The SH exhibits a more limited activity at high and middle latitudes. The Antarctica land-sea interface produces changes in the constant phase lines. Figure 3 shows that in JJA the NH exhibits structures at low and middle latitudes. The whole SH shows a variability of the structures with latitude. During SON Figure 4 shows that there is activity in the NH for $w = 1$, 2 and, 3, mainly at the middle latitudes. The SH exhibits structures at high and middle latitudes. Again, close to the latitude of the Southern border of Africa and Australia, there are noticeable changes of patterns. Along all seasons U structures are generally more oblique than temperature T ones, particularly for w=1. The inclinations in SH and NH are always respectively NW-SE and NE-SW.

3.2. The stratosphere

In Figure 5 for DJF only the NH exhibits structures. The activity is dominated by $w = 1$, where $w = 2$ has a secondary role, both modes mainly at large and middle latitudes. The $w = 1$ features have the largest values of all studied heights and seasons. The U structures undergo a significant longitudinal shift at the land-sea interface at about 65^o latitude. In Figure 6 during the MAM season only $w = 1$ features appear in SH and NH al large and middle latitudes. In the NH, U again undergoes a longitudinal shift at 65^o latitude. In the SH the

U patterns are rather oblique, as in the troposphere. The T features in the SH change angle close to the Antarctic land-sea interface at about -65^o latitude, as in the troposphere. As shown in Figure 7, in JJA there are patterns only in the SH. Again the T features change angle close to the Antarctica land-sea interface and U structures are rather oblique, both characteristics as in the troposphere. The former variable covers low and middle latitudes and the latter one the whole hemisphere. As in MAM, both hemispheres of SON in Figure 8 exhibit activity, but somewhat stronger. The lower halves look similar to JJA (but stronger) and the upper halves to DJF (but weaker). No structures are seen at low latitudes. The $w = 1$ U features are rather oblique, as in the troposphere.

4. Discussion

The weaker planetary wave activity observed in the SH compared to the NH is generally believed to be mainly due to the lower amount of land-sea contrast. We recall that we refer here to seasonally steady planetary structures and that the same holds true. The features observed in this work tend to be predominant in the winter hemisphere and at middle or high latitudes. In particular, the stratosphere exhibits in no season the most intense values at low latitudes and it shows no patterns during the summer. In the troposphere, the largest amount of intense cases may be found at middle latitudes, but in the SH strong activity may also be found close to the Antarctic rim. In addition the latter is the only broad (al least 20^o latitude) permanent pattern in T and U all over the globe. There are no structures at the highest latitudes for U at DJF, but recall that our thresholds for the representation of the modes are partially arbitrary. Significant activity may be found in the troposphere during winter at about the latitudes of the highest mountains (Himalayas in the NH and Andes in the SH) mainly for U, not for T. Some structures seem to have been filtered out at the stratosphere and the picture looks simpler than at the troposphere. In particular, there are no $w = 3$ patterns in any season neither in U nor in T. Wallace and Hsu (1983) provided a theoretical framework in terms of stationary Rossby waves that leads to more restrictive constraints for the development of structures in the stratosphere. However, it could also happen that the numerical model generating reanalysis is not able to reproduce a similar complexity due to its lower reliability and the fact that there are much less observations to be assimilated at these altitudes. The phase lines in T that appear nearly in the same geographical location in the troposphere and stratosphere are about half a cycle out of phase. This relation holds only in some cases for U, where in addition the association between features in the troposphere and stratosphere is more difficult due to the significant inclination of the phase lines.

The tilt in the phase lines, mainly in U, recalls the quasi-stationary Rossby train waves that favor the meridional transport of angular momentum in the global atmosphere. The poleward transfer from low latitudes becomes efficient when the structures have a preferential NE-SW orientation in the NH and opposite in the SH (Starr, 1948; Peixoto and Oort, 1992). The collective effect of this phenomenon all over the globe may be leading to the observed global imprint.

In the troposphere the persistent more oblique nature of the U phase lines as compared to the T ones did not allow any calculation of presumable wave phase differences. This would have been possible only in the stratosphere at about latitude 50^o during DJF and SON, but the bands would have been rather narrow (around 10^o). In addition, the $w = 1$ structures of U in the troposphere have large inclination angles with respect to the meridians, which obscure the visualization of the diverse structures. The general inclination of the phase lines is opposite in both hemispheres and the relation holds for the troposphere and stratosphere.

Zonal structures detected near polar latitudes deserve a particular warning. The convergence of meridians there typically leads to synoptic scale phenomena, so any planetary labeling at large latitudes above is abusive. In addition, the modes detected close to those areas could rather be due to numerical artifacts generated by the large land-sea zonal interfaces rather than true nearly periodic structures.

We now recall previous works that are relevant in relation to our results. Traveling modes detected by some of the earlier investigations on planetary signatures (see e.g. Salby, 1984; Salby and Callaghan, 2001) are out of our scope due to our focus on steady features. Lindzen et al (1982) analyzed with a primitive equation numerical model the stationary planetary waves generated by orographic or thermal forcing. It was found that the response to the latter was sensitive to small changes in the distribution of wind and temperature, which implies that variability in stationary modes can occur even without changes in the forcing itself. Later, Jacqmin and Lindzen (1985) found that at mid-latitudes orographic forcing predominates over the thermal component in the response. They stated that the stratospheric outcome is dominated by topographic sources and its sensivity is much greater than in the troposphere. Steady patterns of $w = 5$ with broad latitudinal extent have been observed in early global analysis data by Salby (1982) in the summer season of the Southern Hemisphere in the mid-latitude troposphere and lower stratosphere. Murgatroyd and O'Neill (1980) made a sound review on the interactions between troposphere and stratosphere.

They outlined that the circulation looks simpler in the stratosphere than in the troposphere and stated that the winter extratropical stratosphere has significant quasi-stationary planetary waves of $w = 1$ and 2. In the Southern Hemisphere stratosphere the perturbations are far less pronounced. The characteristics of the equatorial stratosphere benefit the absorption of the quasi-stationary planetary waves. Tropospheric waves of $w = 1$ and 2 with smaller amplitude than in the upper layer exhibit the same seasonal behavior and may be a determinant factor for the observed stratospheric modes. The degree of vertical penetration of the waves from the troposphere depends on their zonal wavelength, whereby shorter waves find less favorable conditions for propagation. In the Northern Hemisphere, the large-scale mountain ranges are considered the main drivers of the the tropospheric nearly steady waves. Stationary waves of $w > 2$ are of progressively smaller amplitude in the stratosphere. Transient planetary components possess much smaller amplitude than their stationary counterparts in the Northern Hemisphere, but have comparable intensity in the Southern Hemisphere, which could favor a masking effect on the stationary structures in this terrestrial half. Roughly, the overall characteristics of this work are quite well reproduced in our results. The main difference relies in the fact that we have detected some relevant role for $w = 3$ modes. Moreover, in some cases we find that they are comparable to $w = 1$ and 2 structures.

Finally, although waves are often alluded in studies, compliance of observations with wave criteria is often not verifiable or dubious or nonexistent. Our results imply signs of steady structures at planetary scales but no clear indication that they can be called waves. Structures all along the scales that do not definitely meet wave criteria have been found by Lovejoy and Schertzer (2011) in a study of the scaling and cascade properties of diverse meteorological fields and fluxes from European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalyses. In general, planetary signatures may be better conceptualized as disturbances about the zonal mean circulation, which are not necessarily a wave. These perturbations can be mainly produced by two mechanisms: orographic forcing or differential heating (Salby, 1984). Stationary structures may be forced by mechanical or thermal sources anchored to the surface of the Earth. Topography can produce disturbances either by flow forcing or as elevated heat sources. Thermal forcing may be also associated with land-sea transitions or sea surface temperature gradients. The planetary distribution of these sources may ultimately determine the typical space scales of the disturbances.

5. Conclusions

Significant wavenumber 1 and 2 seasonally steady structures in zonal velocity and temperature have been found in 30 years of reanalysis data at the middle troposphere (400 hPa) and middle stratosphere (10 hPa) respectively. Wavenumber 3 structures also appear at 400 hPa. The zonal wind 1 modes exhibit significant inclination angles with respect to the meridians. The winter hemisphere shows stronger activity, whereby the NH exhibits a larger amount of structures and more intense amplitudes than the SH. Middle latitudes exhibit the most significant cases and low latitudes the least significant ones. Longitudinally oriented land-sea transitions at $\pm 65^o$ and -35^o latitudes appear to play a significant role for the presence of steady planetary structures. The stratosphere exhibits a much simpler picture than the troposphere. There are possible theoretical explanations for this characteristic, but this fact may also be due to the lower reliability of the numerical model of reanalysis in describing the stratosphere and to the smaller amount of data being assimilated at these altitudes. Large scale structures with respectively NE-SW (NH) and NW-SE (SH) tilts in the observed T and U phase lines recall the quasi-stationary Rossby wave trains that favor the poleward transport of angular momentum. It must be finally stated that the observed planetary structures do not exhibit fulfillment of wave criteria, but similar behavior has already been found in previous works.

Acknowledgements Manuscript prepared under grant UBA X004. P. Alexander is a member of CONICET. The data used in this study are from the NCEP/NCAR reanalyses, obtained from the Climate Diagnostics Center in Boulder, Colorado www.cdc.noaa.gov.

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Figure Captions

Figure 1. Localization of maxima (black) and minima (white) of modes $w = 1$ (x), 2 (+) and 3 (*) according to Fourier analysis at each latitude of reanalysis data at 400 hPa during season DJF averaged over years 1979-2008: a) temperature, b) zonal velocity. The size of the symbols along Figures 1 to 8 is proportional to the amplitude of oscillation (1 K - 11 K for temperature and 2 m/s - 26 m/s for zonal velocity).

Figure 2. Same as Figure 1 but for season MAM.

Figure 3. Same as Figure 1 but for season JJA.

Figure 4. Same as Figure 1 but for season SON.

Figure 5. Same as Figure 1 but for 10 hPa.

Figure 6. Same as Figure 5 but for season MAM.

Figure 7. Same as Figure 5 but for season JJA.

Figure 8. Same as Figure 5 but for season SON.

Figure 1

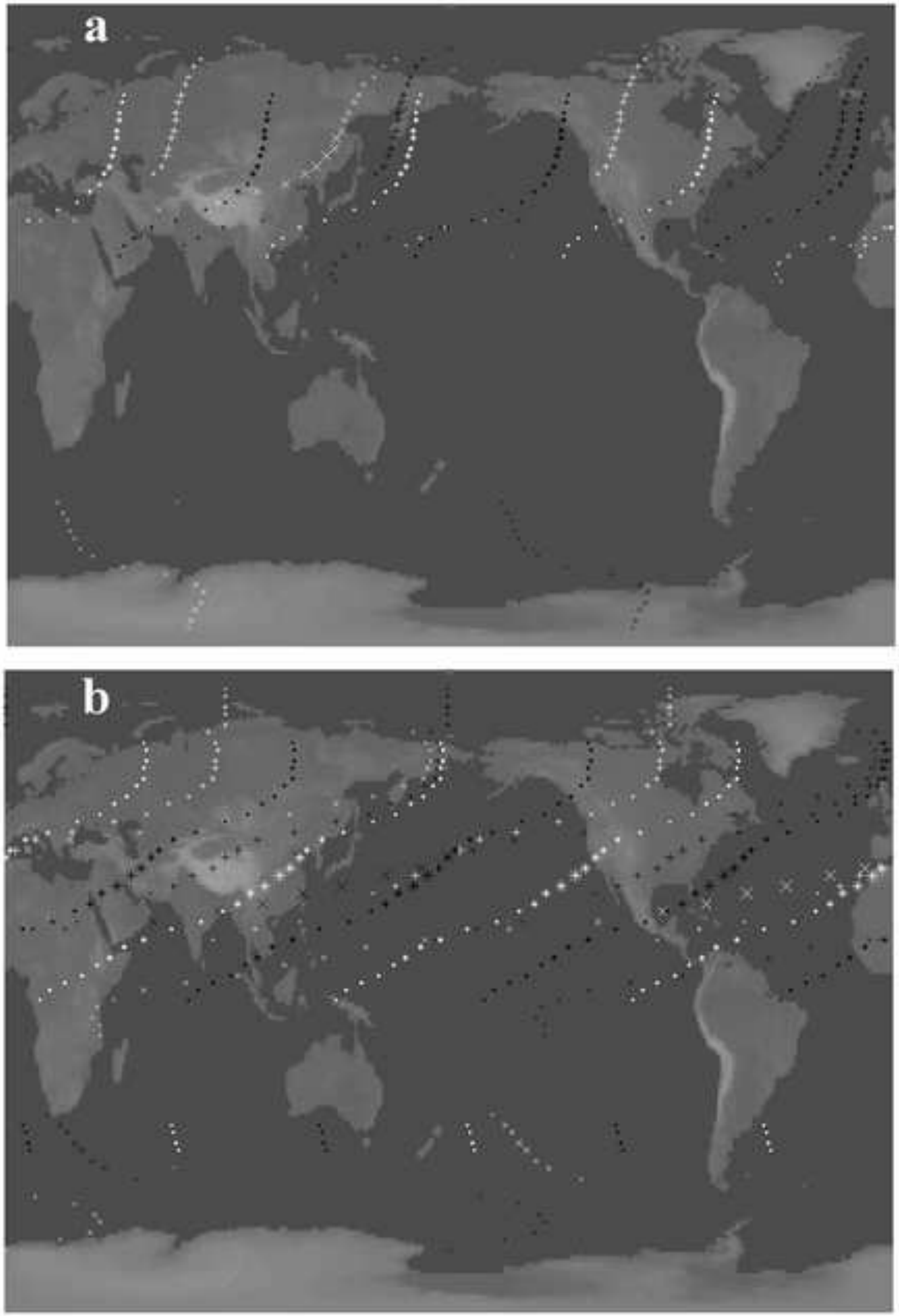


Figure 2

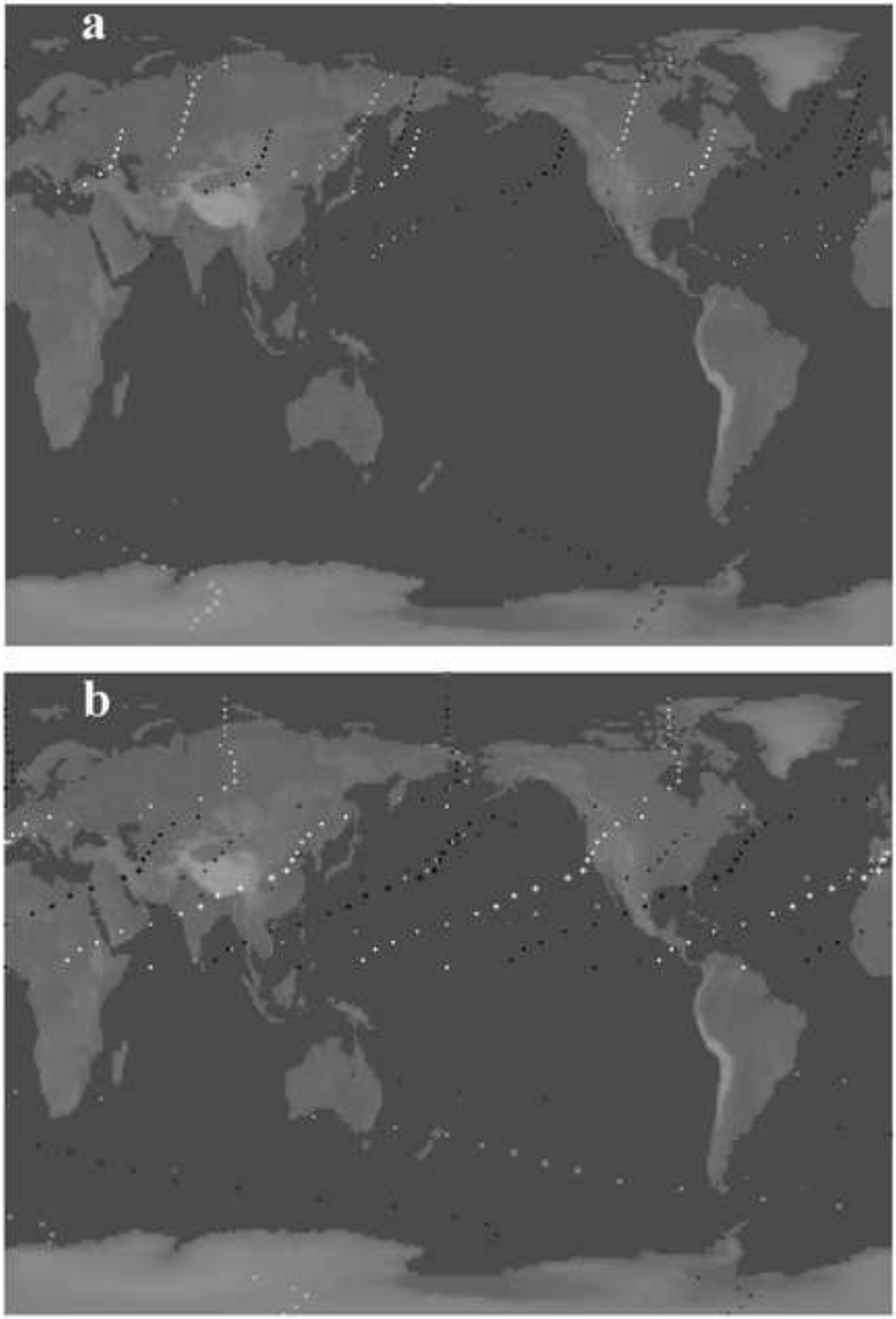


Figure 3

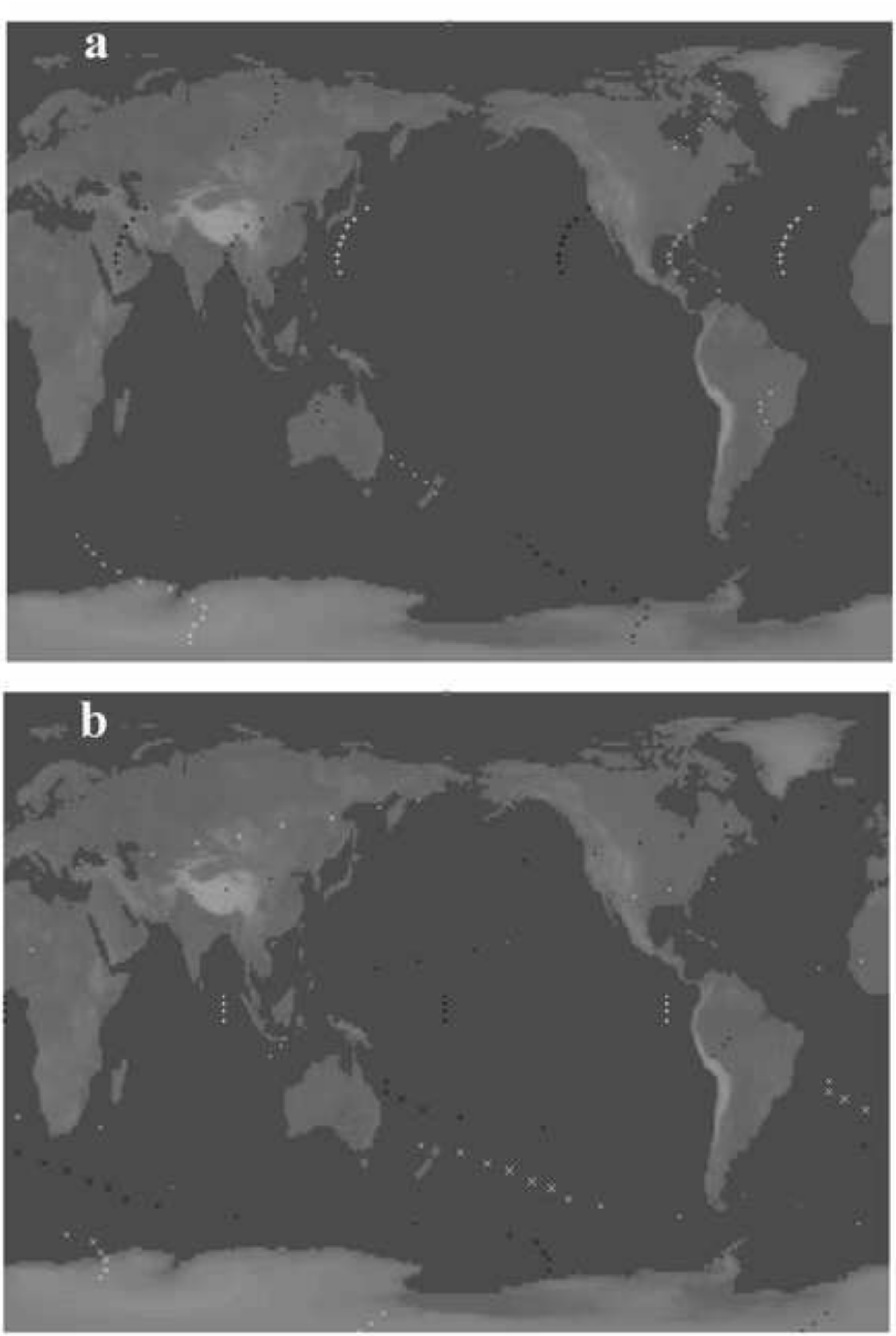


Figure 4

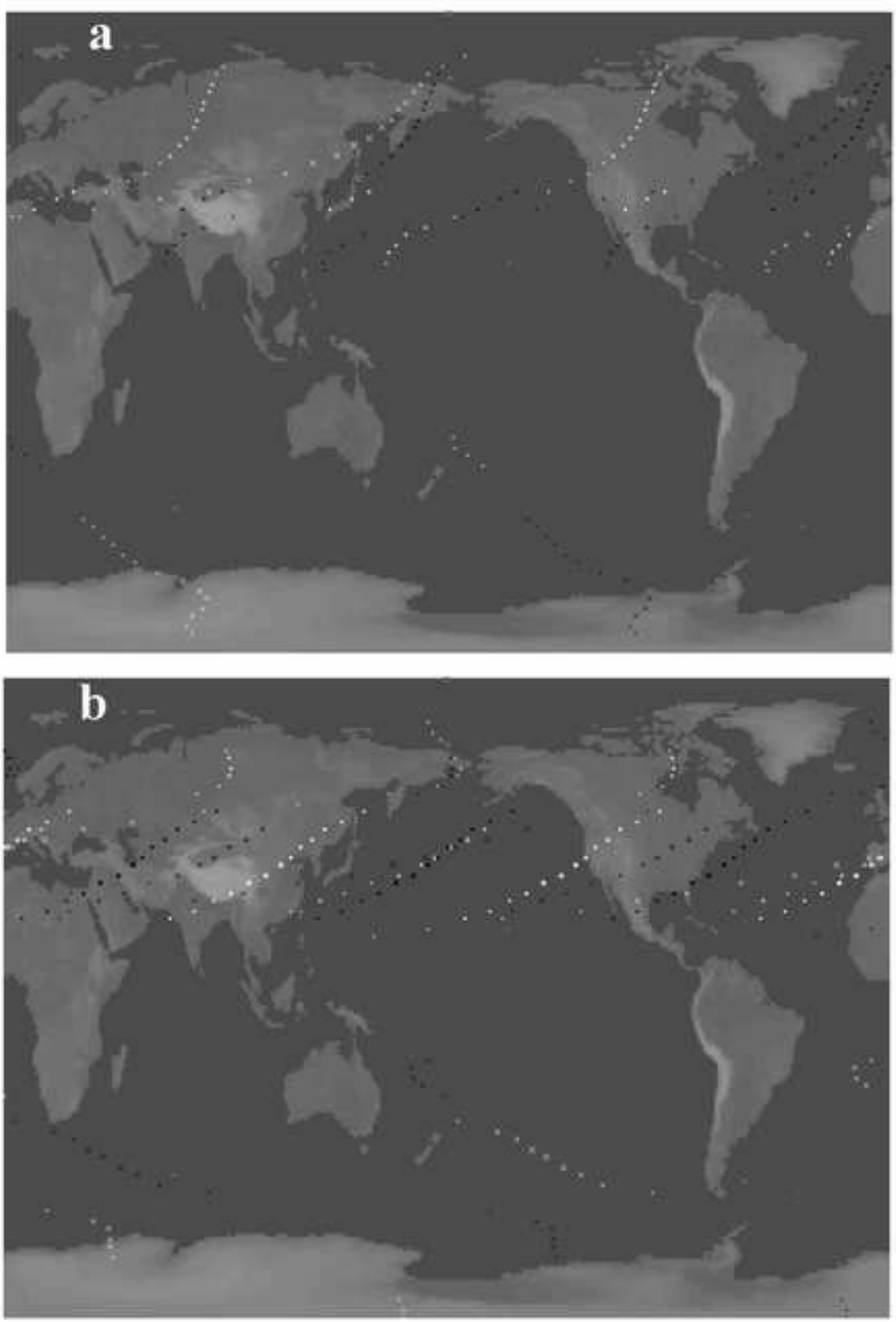


Figure 5

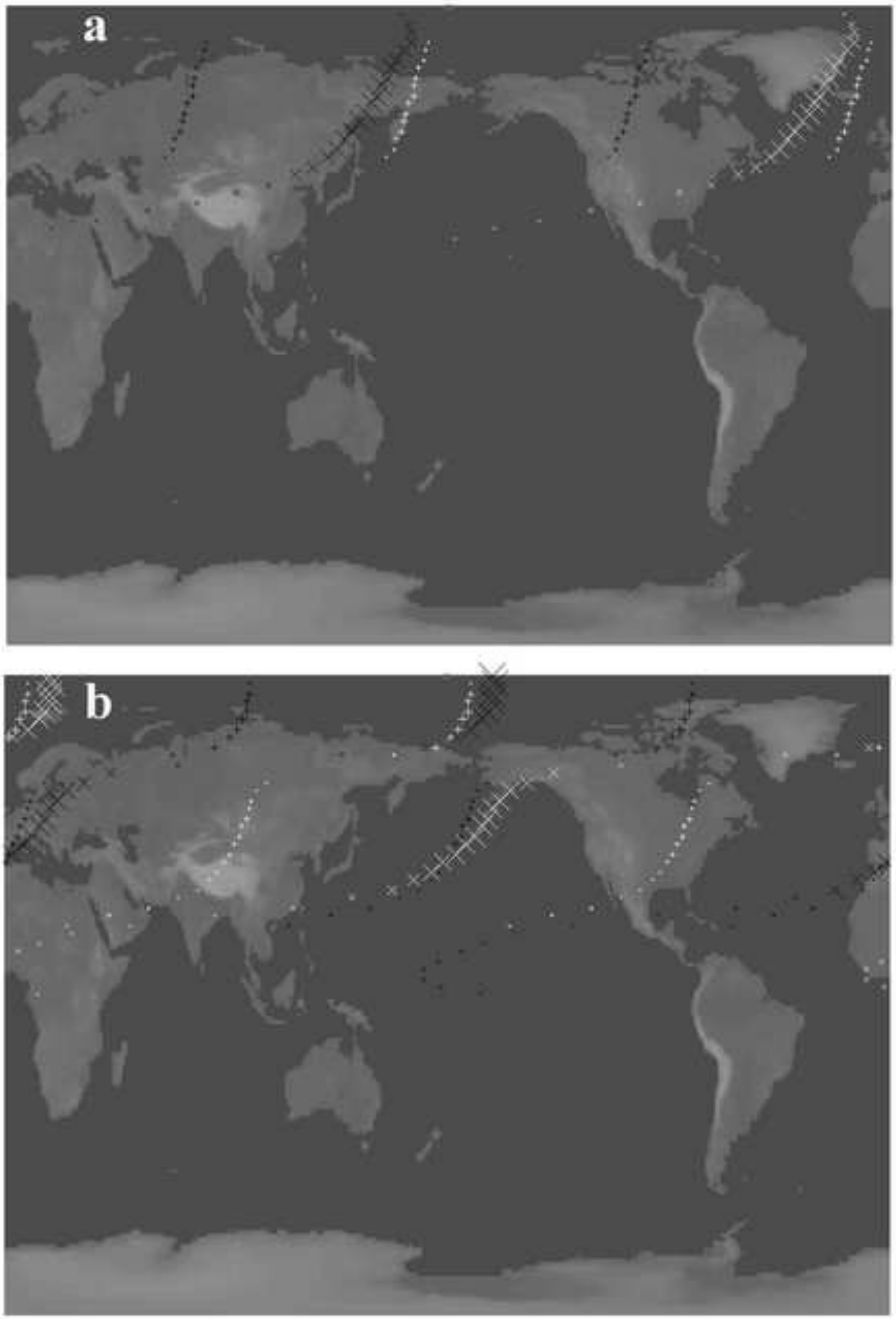


Figure 6

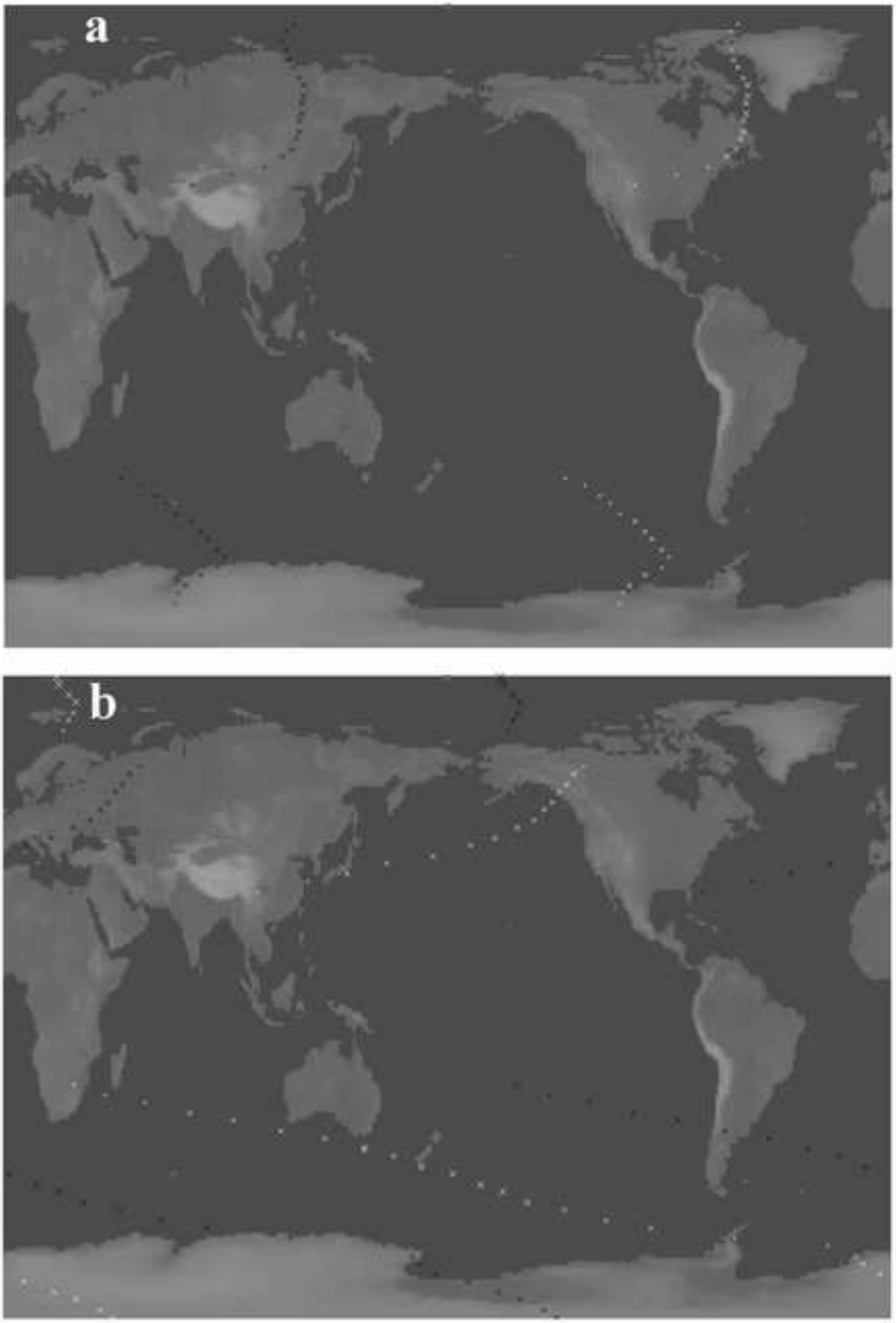


Figure 7

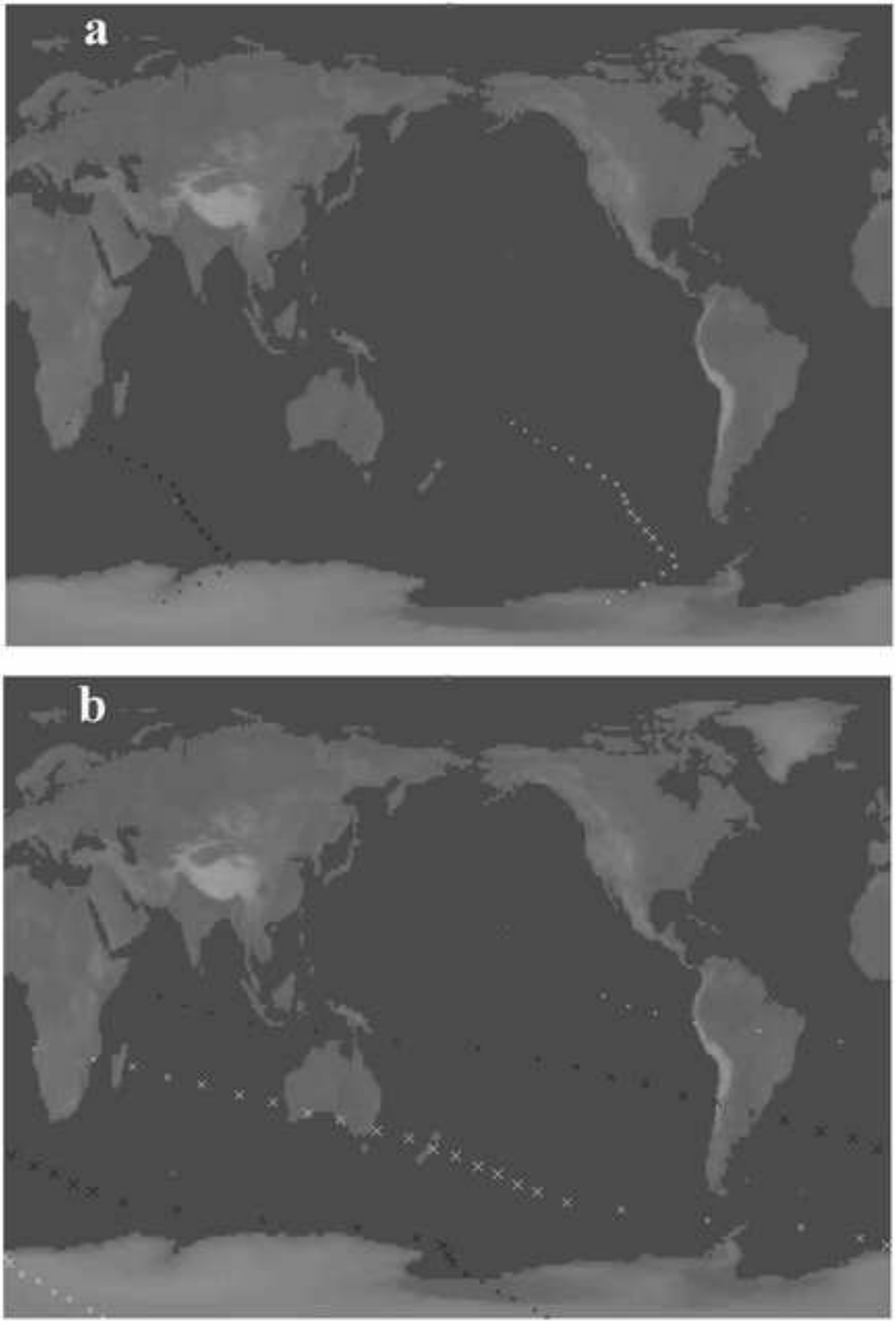
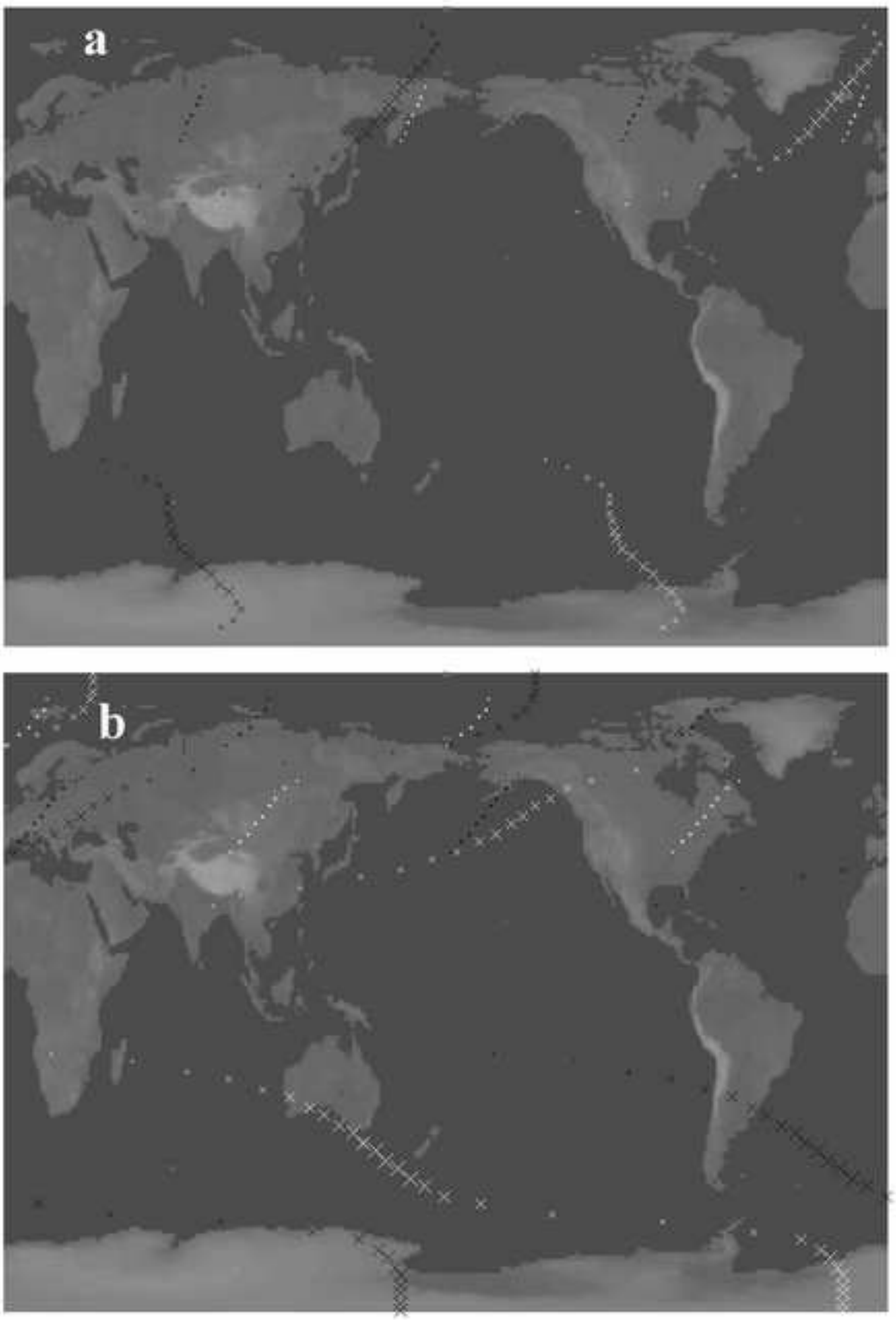


Figure 8



*Detailed Response to Reviewers

Reviewer 1

Paragraph 1: please see page 7 (middle paragraph), the paragraph on page 14 and the last sentence of Conclusions in the new version of the manuscript.

Paragraph 2: please see the paragraph spanning the pages 12-14 of the new version of the manuscript.

Paragraph 3: please see the last paragraph on page 11 of the new version of the manuscript.

Reviewer 3

> 1. I do not understand the sentence on line 159 "There are only no
> symbols at the highest latitudes .". Would you like to say "There are no
> structure sat the highest latitudes ." or what do you mean?

We followed your suggestion, please see line 168 of the new version of the manuscript.

> 2. Lines 193-195: This statement is not correct. Significant wavenumber
> 3 does not appear at 10 hPa.

We reformulated the sentence, please see lines 260-263 of the new version of the manuscript.

> 3. Wording and misprints:
> - Lines 114, 120 and 125: "large" should be "high".
> - Line 116: write "in zonal wind (U) the features".
> - Line 128: write "than temperature (T) ones".

Please see lines 123, 129, 134, 125 and 137 of the new version of the manuscript.