**Abstract and Conclusion**

The processes and tests applied in the intermediate validation of the product

**SW\_OPER\_MIO\_SHAi2C\_00000000T000000\_99999999T999999\_0501**

and the conclusions on the product quality drawn herefrom are described in this document.

This product contains the representation of a model of the magnetic field of Earth’s ionosphere (“MIO” part of product name) using spherical harmonic coefficients (“SHA” part of product name). The model is estimated from Swarm and ground observatory data using the *Comprehensive Inversion* (CI) scheme within the Swarm Level 2 Processing system (“2C” part of product name). Operational Swarm Level 1b data version 0505/06, covering the period from 2013-11-25 to 2018-12-31 are used for the model estimation and the product is considered valid at all times (“00000000T000000\_99999999T999999” part of product name). This is version 0501 of the product (last part of product name), i.e. baseline 05 indicating 5th year CI production, first, minor version. The format of the product is described in “Product Specification for L2 Products and Auxiliary Products”, doc. no. SW-DS-DTU-GS-0001.

The assessment of the product shows structures in good agreement with ionospheric field models.

**The DTU SIL’s opinion is that the MIO\_SHAi2C product is successfully validated and therefore suitable for release.**

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Abbreviations

| ***Acronym*** | ***Description*** |
| --- | --- |
| AR-2 | Acceptance Review 2 |
| CI | Comprehensive Inversion |
| CMB | Core-Mantle Boundary |
| DIFI | Dedicated Ionospheric Field Inversion |
| L2PS | Level 2 Processing System |
| MIO | Magnetic Ionospheric field |
| QD | Quasi Dipole |
| SHA | Spherical Harmonic Analysis |
| SIL | Scientist in the Loop |
| STR | Star Tracker |
| TDS | Test Data Set |
| VAL | Validation |
| VFM | Vector Field Magnetometer |

References

[Sabaka, GJI, 2004] *Extending comprehensive models of the Earth's magnetic field with Orsted and CHAMP data*; Sabaka, Terence J.; Olsen, Nils; Purucker, Michael E.; in journal: Geophysical Journal International (ISSN: 0956-540X), vol: 159, issue: 2, pages: 521-547, 2004.

[Sabaka et.al., GJI, 2015] *CM5, a pre-Swarm comprehensive geomagnetic field model derived from over 12 yr of CHAMP, Ørsted, SAC-C and observatory data*; Sabaka, Terence J.; Olsen, Nils; Tyler, Robert H.; Kuvshinov, Alexey; in journal: Geophysical Journal International (ISSN: 0956-540X), vol: 200, issue: 3, pages: 1596-1626 (2015) , doi: [10.1093/gji/ggu493](http://dx.doi.org/10.1093/gji/ggu493).

[Sabaka et.al., GRL, 2016] *Extracting Ocean-Generated Tidal Magnetic Signals from Swarm Data through Satellite Gradiometry*; Sabaka, Terence J. ; Tyler, Robert H. ; Olsen, Nils in journal: Geophysical Research Letters (ISSN: 0094-8276) (2016), doi: [10.1002/2016GL068180](http://dx.doi.org/10.1002/2016GL068180).

[Sabaka et.al., EPS, 2018] *A Comprehensive Model of Earth's Magnetic Field Determined From 4 Years of Swarm Satellite Observation*; Sabaka, Terence J. ; Tøffner-Clausen, Lars; Olsen, Nils; Finlay, Christopher C. , in Earth, Planets and Space, vol: 70, issue: 1 (2018), doi: [10.1186/s40623-018-0896-3](https://doi.org/10.1186/s40623-018-0896-3).

# Intermediate Validation Report of

## Input data products

The following input data products were used for the estimation of the ionospheric field model

| **Products** | **Type** | **Period** | **Comment** |
| --- | --- | --- | --- |
| SW\_OPER\_Q3D\_CI\_i2\_\_00000000T000000\_99999999T999999\_0101 | Q-matrix of Earth’s electrical conductivity (1-D mantle + oceans) | - | Used for computing induced part of ionospheric field |
| SW\_OPER\_AUX\_OBS\_2\_\_20130101T000000\_20131231T235959\_0117 SW\_OPER\_AUX\_OBS\_2\_\_20140101T000000\_20141231T235959\_0117 SW\_OPER\_AUX\_OBS\_2\_\_20150101T000000\_20151231T235959\_0117 SW\_OPER\_AUX\_OBS\_2\_\_20160101T000000\_20161231T235959\_0117 SW\_OPER\_AUX\_OBS\_2\_\_20170101T000000\_20171231T235959\_0117  SW\_OPER\_AUX\_OBS\_2\_\_20180101T000000\_20181231T235959\_0117 | Observatory hourly mean values | 2013-11-25 – 2018-10-31 | A total of 163 observatories are included |
| SW\_OPER\_AUX\_DST\_2\_\_19980101T013000\_20190115T233000\_0001 SW\_OPER\_AUX\_F10\_2\_\_20060101T000000\_20190115T000000\_0001 SW\_OPER\_AUX\_KP\_\_2\_\_19990101T023000\_20190117T133000\_0001 | Indices | As indicated by the file names |  |
| SW\_OPER\_MAGA\_LR\_1B\_*yyyymmdd*T*h1m1s1*\_*yyyymmdd*T*h2m2s2*\_*vvvv* SW\_OPER\_MAGB\_LR\_1B\_*yyyymmdd*T*h1m1s1*\_*yyyymmdd*T*h2m2s2*\_*vvvv* SW\_OPER\_MAGC\_LR\_1B\_*yyyymmdd*T*h1m1s1*\_*yyyymmdd*T*h2m2s2*\_*vvvv* | Swarm magnetic data, 1 Hz | 2013-11-25 - 2018-12-31 | Decimated to 30 second sampling *vvvv* = 0505 or 0506 |

Table 1‑1: Input data products

## Model Parameterization and Data Selection

See Section 2.1.

## Output Products

The products of this validation report are:

*Swarm Level 2 Magnetic ionospheric field Product:*

*Swarm Level 2 Intermediate Validation Product:*

SW\_OPER\_MIO\_VALi2CSW\_OPER\_MIO\_SHAi2C\_00000000T000000\_99999999T999999\_0501

## Validation Results

The tests were conducted between 2019-01-15 and 2019-02-10.

This 5th year CI L2 production, denoted CIY5, is very similar in methodology and results as last year’s production (CIY4) which is thoroughly described in [Sabaka et.al., EPS, 2018]. The following contains the results of the tests performed on the ionospheric field output product. See Annex A for general definitions of various tests. See Annex A for general definitions of various tests.

### Equivalent Current Function

The figures on the following pages show the equivalent current function of the primary ionospheric currents for the product and for the CM5 model [Sabaka et.al., GJI, 2015] for four different epochs, for the equinoxes and the solstices. Each plot shows the current system for four different UT times, morning (06h), noon, evening (18h), and midnight. The blue line indicates the magnetic dip equator, which gives an indication of the separation between northern and southern current functions. Also shown are the 55°N and 55°S magnetic quasi dipole latitudes in red corresponding to the transition of the use of vector field information. The current function is shown as iso-lines with 10 kA separation.

Figure 1‑1: Equivalent current function, CIY5, March equinox

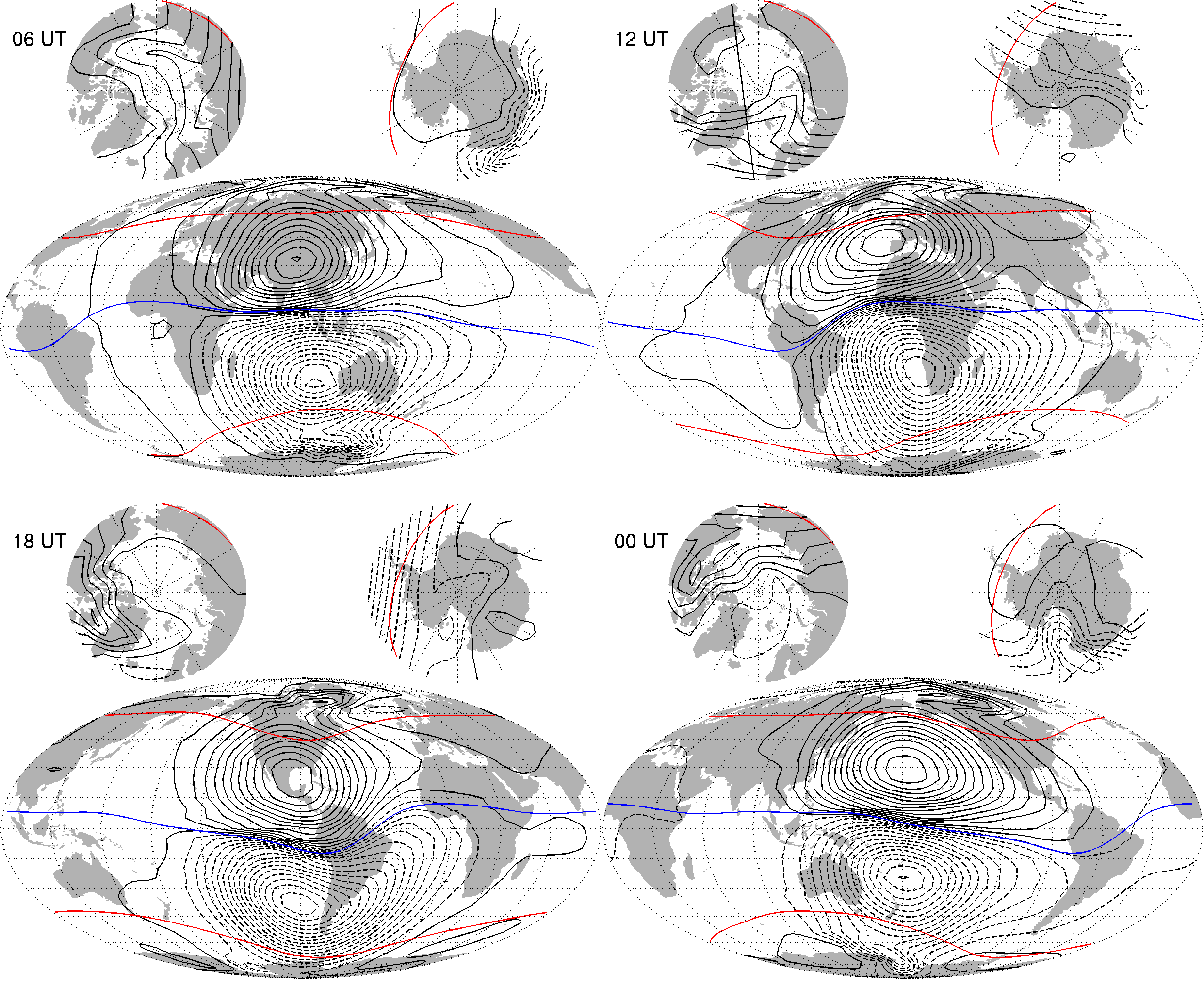
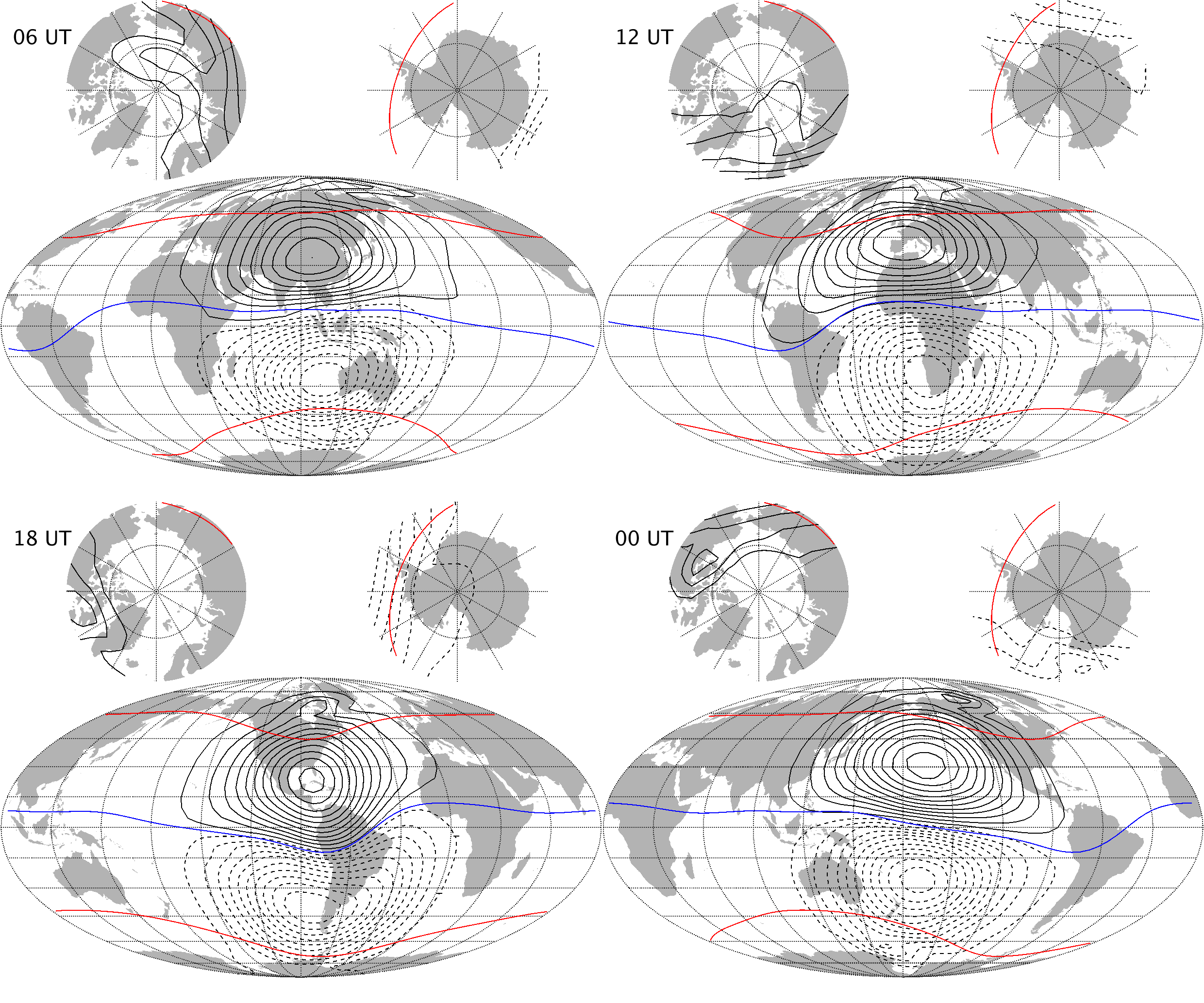


Figure 1‑2: Equivalent current function, CM5, March equinox

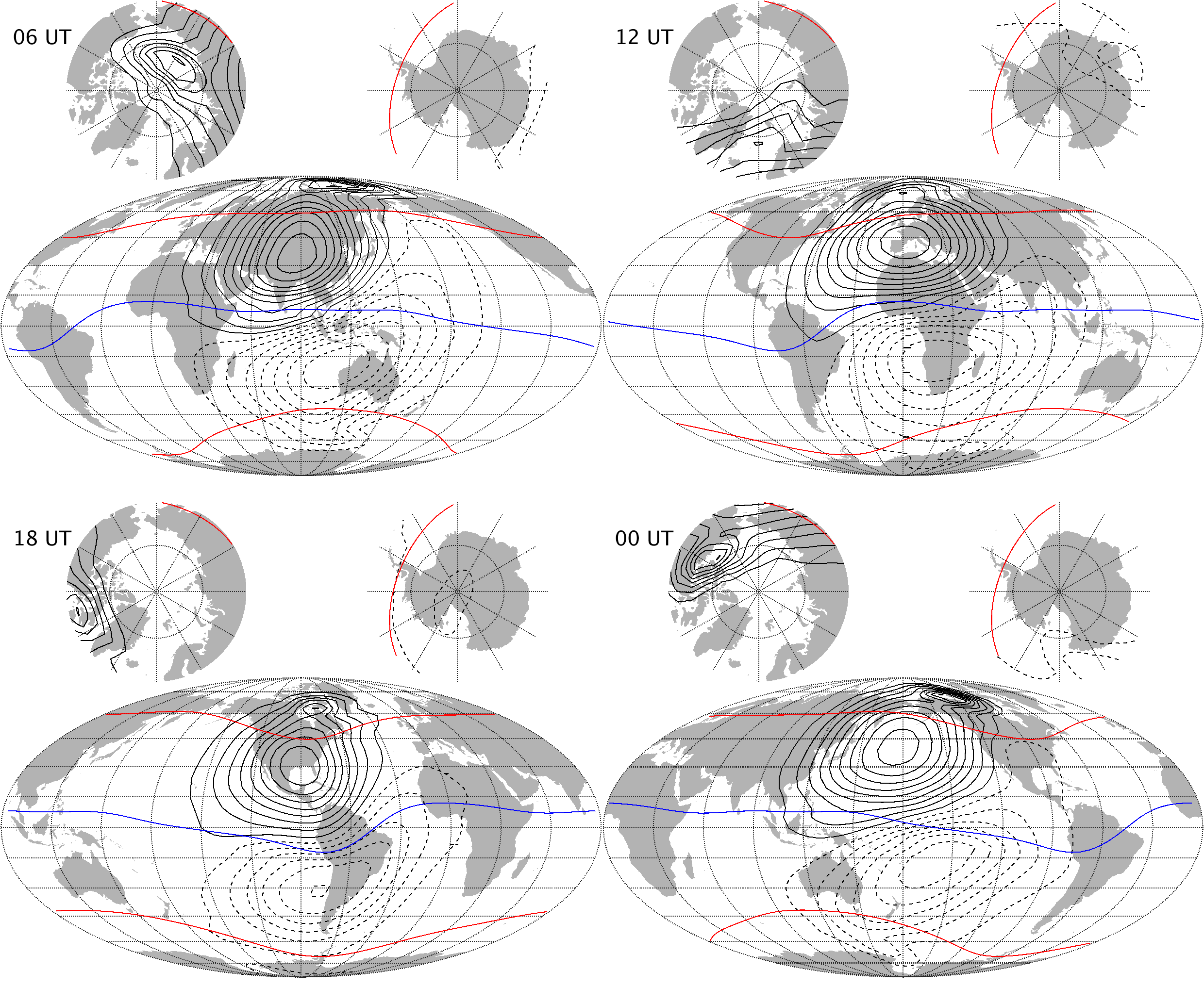


Figure 1‑3: Equivalent current function, CIY5, June solstice

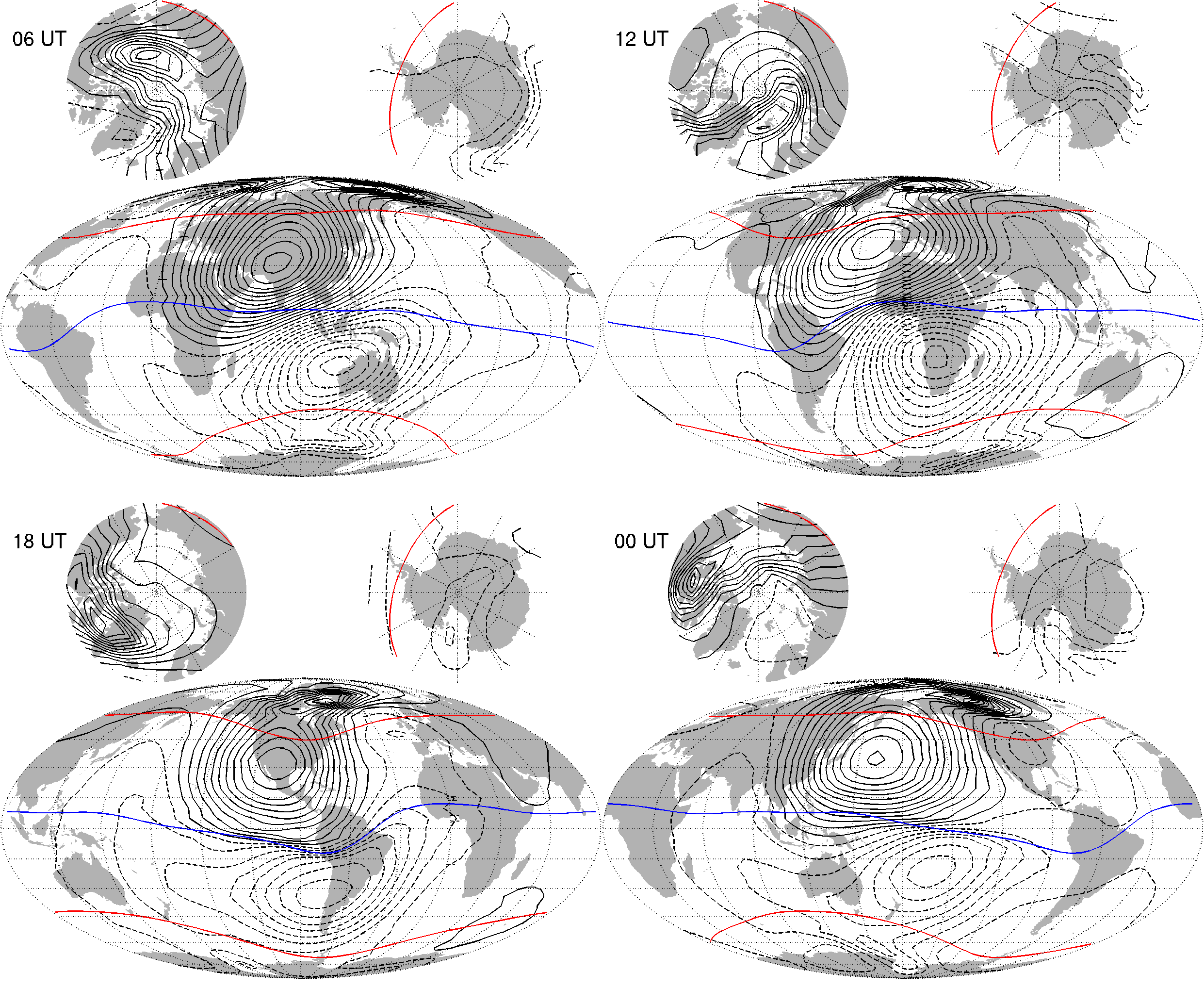


Figure 1‑4: Equivalent current function, CM5, June solstice

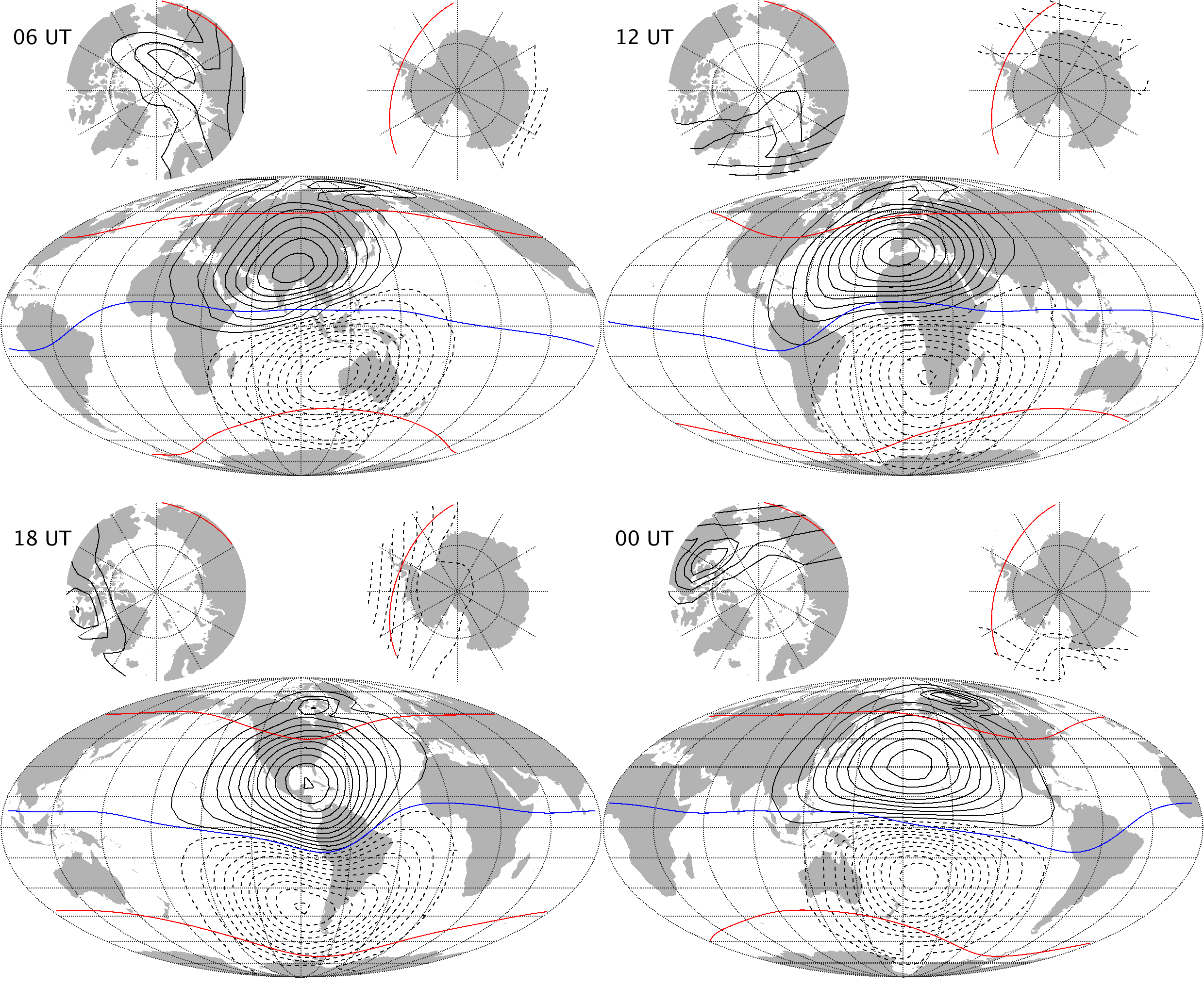


Figure 1‑5: Equivalent current function, CIY5, September equinox

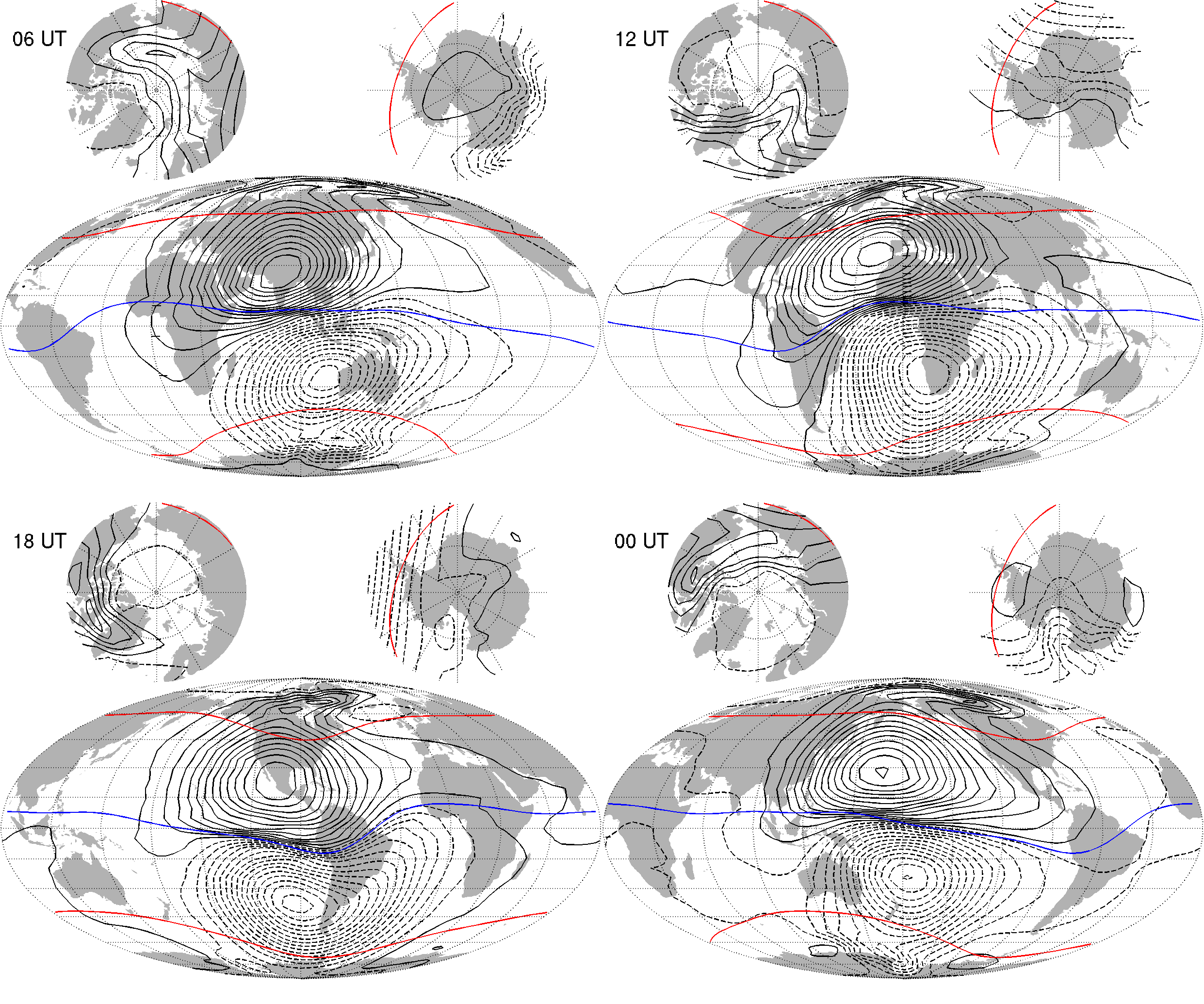


Figure 1‑6: Equivalent current function, CM5, September equinox

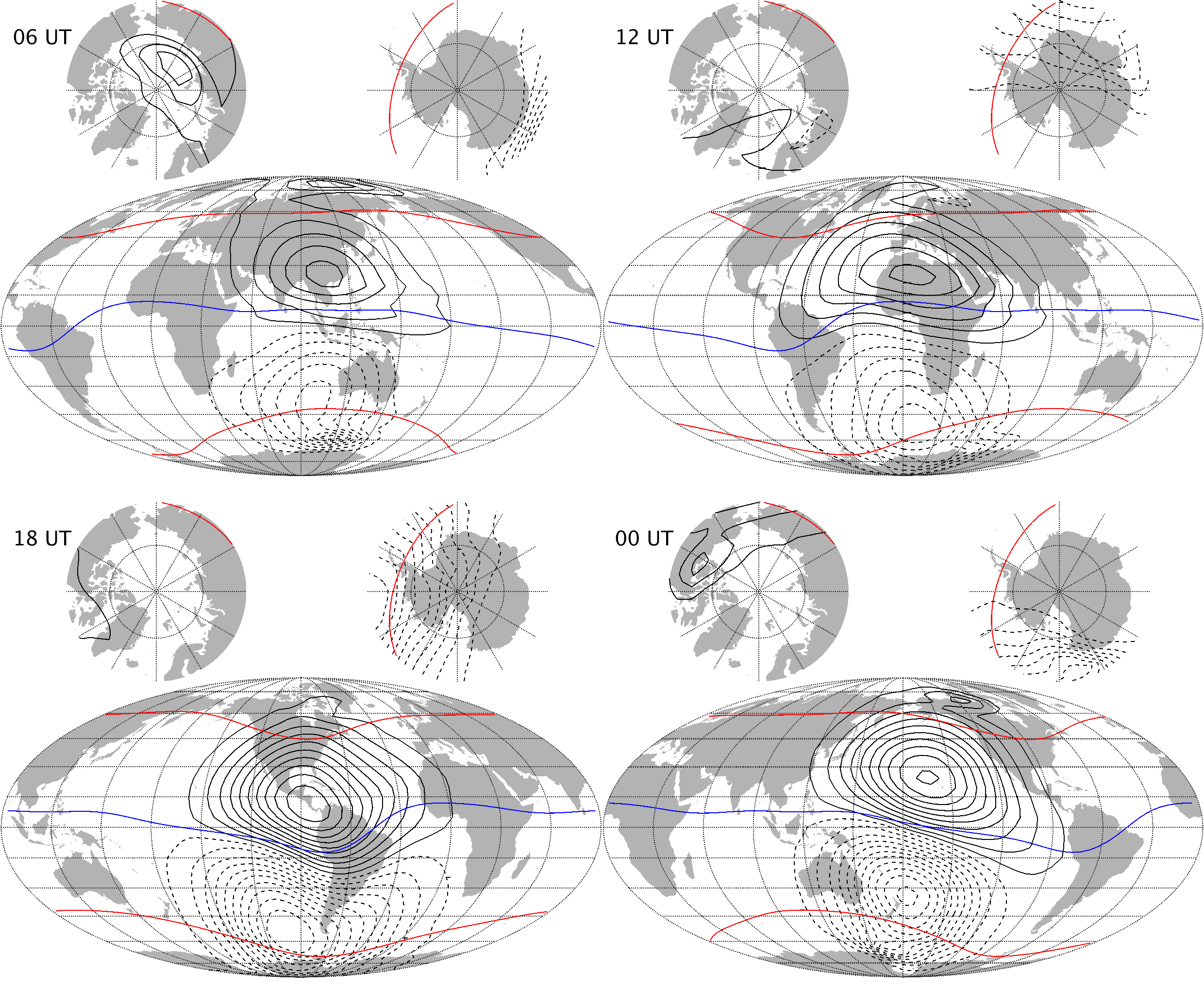


Figure 1‑7: Equivalent current function, CIY5, December solstice

Figure 1‑8: Equivalent current function, CM5, December solstice

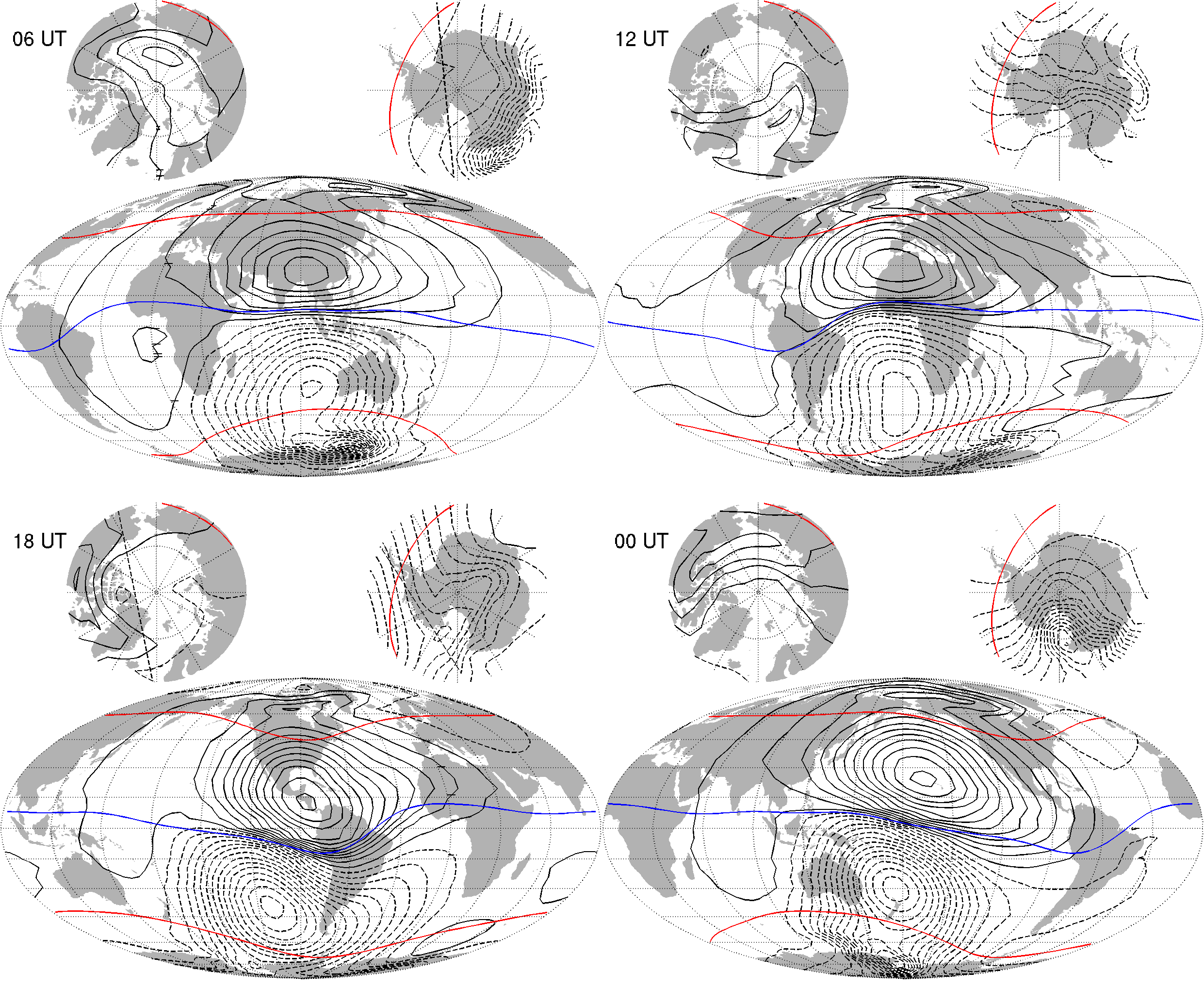


Figure 1‑9 on the next page shows maps of the radial magnetic field component at ground of the CIY4 ionospheric model (top four plots) and of the Dedicated Ionospheric Field Inversion (DIFI) model (bottom four plots) for the September equinox at four local times. Ground observatories used in the CIY4 model are indicated in green. Although the DIFI model fits the ground observatory data better than the CIY4 model (cf Table 1‑2 on page 16) the many small structures observed in the DIFI model are believed to be unrealistic for the magnetic field from sources in the ionosphere. Conversely, the CIY4 model is likely too smooth compared to the true structure of the ionospheric field.

Figure 1‑9: Radial magnetic field at ground, CIY4 (top four) and DIFI (bottom four), September equinox

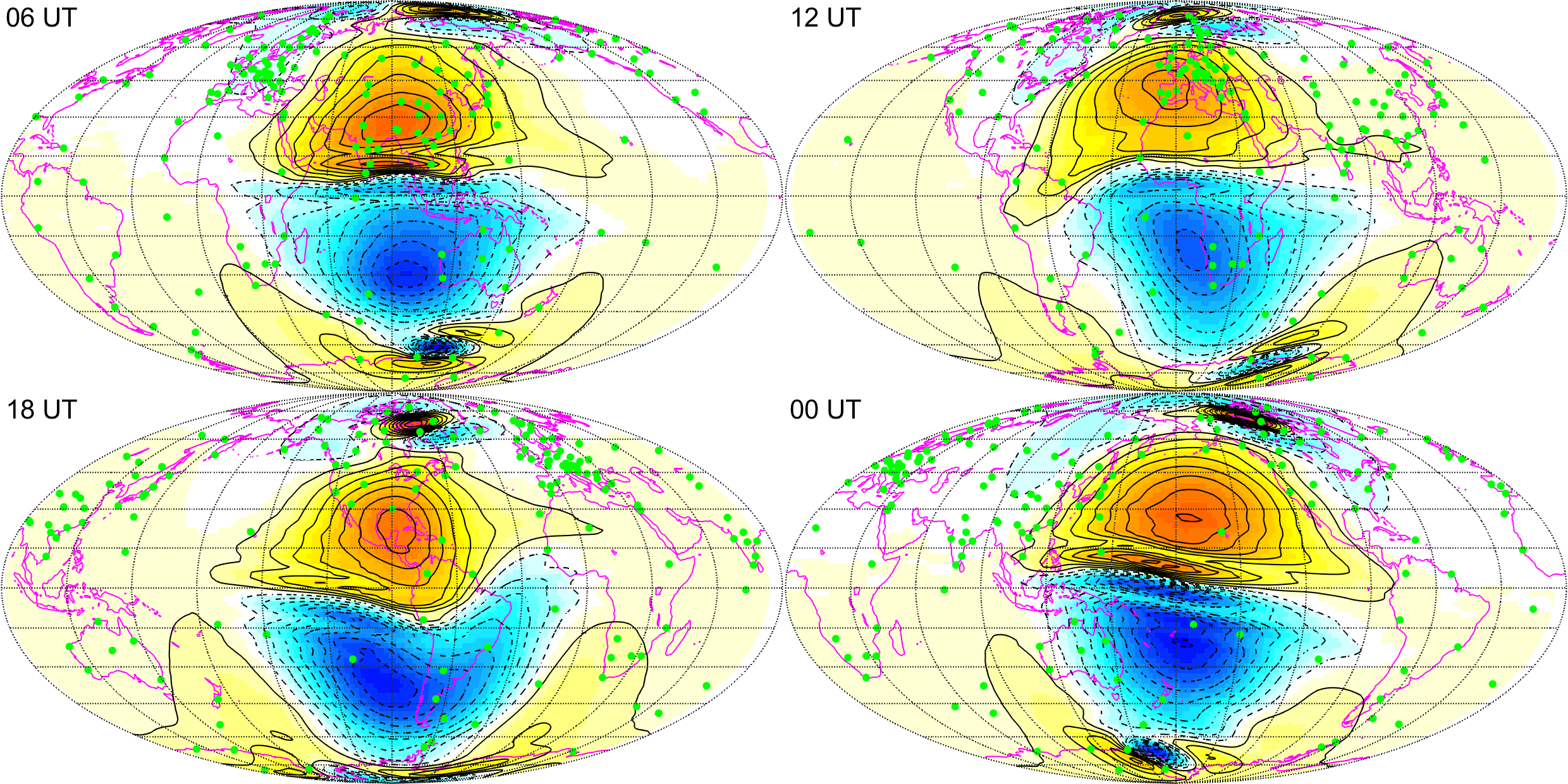
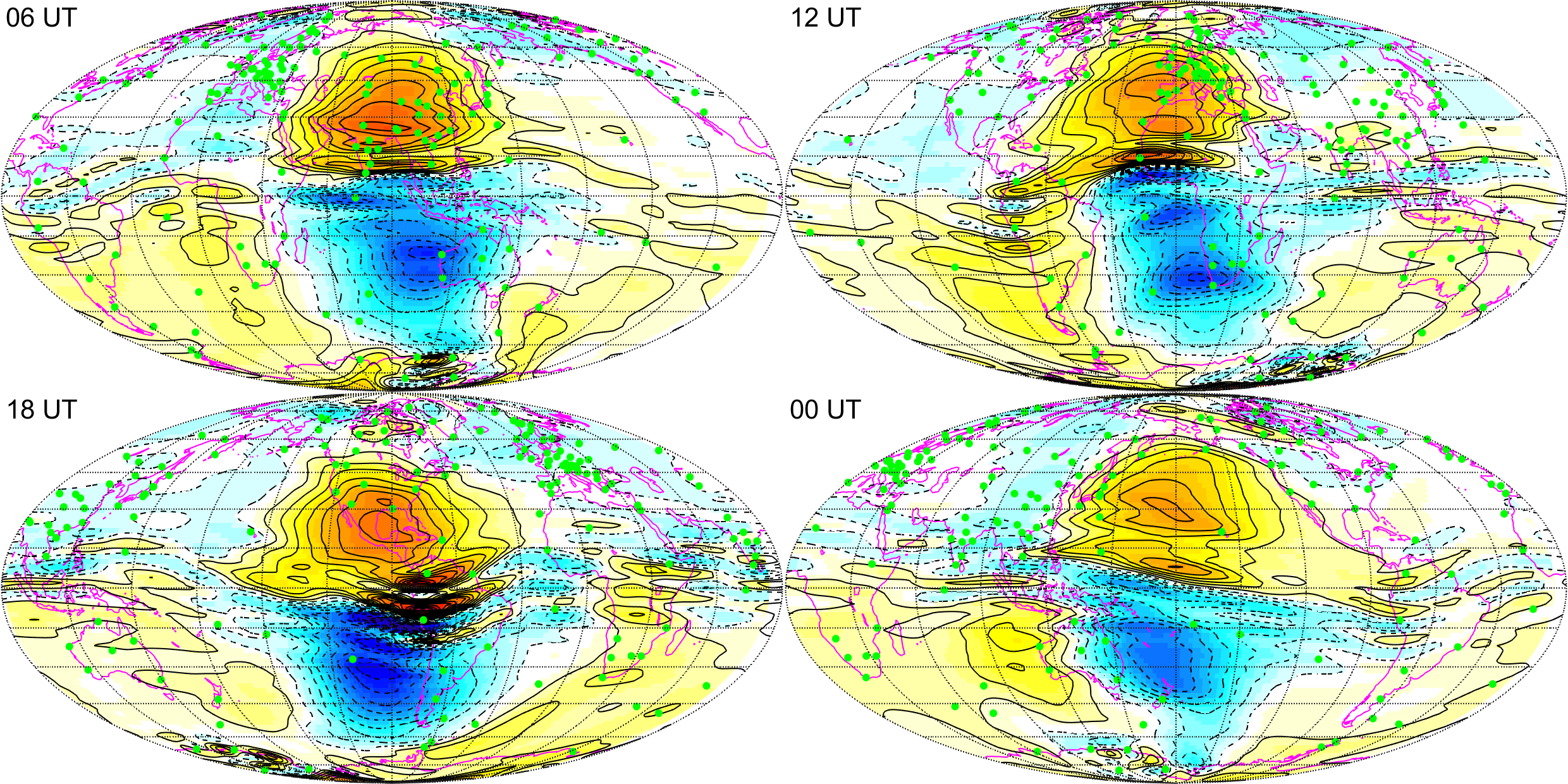


Table 1‑2 below contains the Huber weighted rms values of the mid-latitude (QD latitude between 10° and 55°) ground observatory data residuals versus the complete CIY4 model and versus CIY4 with DIFI substituted for the ionospheric contribution. The DIFI model yields slightly smaller residual than CIY4 due to its better fit to the ground observatory data accomplished through a model with many small scale structures.

| **Model** | **Night side** | | | **Day-side** | | |
| --- | --- | --- | --- | --- | --- | --- |
| Standard deviations of observatory data residuals, Huber weighted, [nT] | | | | | |
| σ(Br) | σ(Bθ) | σ(Bφ) | σ(Br) | σ(Bθ) | σ(Bφ) |
| CIY4 | 3.78 | 4.45 | 5.06 | 5.61 | 7.01 | 8.30 |
| DIFI | 3.66 | 3.51 | 3.81 | 5.02 | 5.90 | 6.06 |

Table 1‑x: Residual statistics of mid-latitude observatory data, CIY4 and DIFI

### Statistics of Model Residuals

The statistics of the data residuals obtained by the CIY5 modelling is given in Table 1‑3 below. Grey cells indicate data from night side, white cells indicate data from sunlit regions. Crossed cells indicate data which are not used in the inversion process. “Field” indicate the pure vector and scalar measurements, whereas “NS diff” and “EW diff” indicate the North-South (along-track) respectively East-West differences. The standard deviations (of the residuals between the observations and the estimated model) of the differences are quite impressive; the standard deviations of the direct field measurements from the satellites are also remarkably. Note in addition the almost perfect similarity between Swarm A and C (side-by-side flying pair) and North-South differences for all three satellites. As also expected, Swarm B shows slightly higher residuals in the horizontal and scalar Field components (Bθ, Bφ, and F) at low and mid latitudes and slightly lower residuals at high latitudes likely due to its higher altitude due to its higher altitude.

| Swarm/ Obs. | | Geomagnetic quasi-dipole latitude | | | | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Low, ≤ 10° | | | | Mid, ]10°..55°] | | | | High, > 55° | | | |
| Standard deviations of data residuals, Huber weighted, [nT] | | | | | | | | | | | |
| σ(Br) | σ(Bθ) | σ(Bφ) | σ(F) | σ(Br) | σ(Bθ) | σ(Bφ) | σ(F) | σ(Br) | σ(Bθ) | σ(Bφ) | σ(F) |
| A | Field | 1.63 | 1.92 | 1.66 | 2.41 | 1.65 | 2.09 | 2.07 | 1.78 |  |  |  | 5.62 |
| NS diff | 0.31 | 0.18 | 0.32 | 0.16 | 0.24 | 0.28 | 0.35 | 0.18 |  |  |  | 0.93 |
| 0.89 | 0.76 | 0.79 | 0.68 | 0.49 | 0.53 | 0.82 | 0.31 |  |  |  | 1.05 |
| B | Field | 1.64 | 2.49 | 1.98 | 3.29 | 1.88 | 2.55 | 2.26 | 2.33 |  |  |  | 5.44 |
| NS diff | 0.30 | 0.18 | 0.30 | 0.16 | 0.24 | 0.28 | 0.34 | 0.19 |  |  |  | 0.83 |
| 0.80 | 0.67 | 0.72 | 0.60 | 0.47 | 0.52 | 0.80 | 0.29 |  |  |  | 0.95 |
| C | Field | 1.64 | 1.87 | 1.64 | 2.38 | 1.65 | 2.08 | 2.07 | 1.78 |  |  |  | 5.62 |
| NS diff | 0.32 | 0.18 | 0.32 | 0.16 | 0.25 | 0.29 | 0.35 | 0.18 |  |  |  | 0.93 |
| 0.90 | 0.76 | 0.78 | 0.68 | 0.49 | 0.54 | 0.82 | 0.31 |  |  |  | 1.05 |
| A-C | EW diff | 0.55 | 0.40 | 0.74 | 0.36 | 0.38 | 0.44 | 0.75 | 0.32 |  |  |  | 0.55 |
| 1.22 | 0.63 | 1.79 | 0.51 | 0.70 | 0.75 | 1.50 | 0.44 |  |  |  | 0.59 |
| Magnetic observatories | | 3.99 | 4.01 | 4.50 | n.c. | 3.44 | 3.87 | 4.31 | n.c. | 13.23 | 12.83 | 10.41 | n.c. |
| 11.41 | 13.43 | 9.39 | n.c. | 5.31 | 6.75 | 7.97 | n.c. | 16.26 | 17.37 | 15.07 | n.c. |

Table 1‑2: Statistics of model residuals

## Criteria

Table 1‑4 below summarizes the criteria used to check the validity of the product:

| **Input** | **Test** | **Criteria** | **Pass?** |
| --- | --- | --- | --- |
| Observations | Residual statistics | Standard deviation of vector data below 7 nT.  Standard deviation of scalar data below 5 nT | Ok |
| Satellite Observations | Residual plots | Residuals show expected behaviour | Ok |
| Alternative model | Comparison with model | CI model agrees with alternative model | Ok |
| Reference model | Accumulated error of secular variation | Below threshold requirement, 3 nT/yr | Ok |

Table 1‑3: Validation criteria

# Additional Information

## Model Configuration and Data Selection Parameters

The product is obtained as a comprehensive co-estimation of the core, lithosphere, ionosphere, and magnetosphere field contributions including induced contributions similar to the method described in [Sabaka et.al., GRL, 2016]. The complete model configuration used is given in Table 2‑1 below; the product is the green part:

| **Model Part** | **Maximum Degree/Order** | **Temporal Characteristics** | **Comment** |
| --- | --- | --- | --- |
| Core | 18/18 | Order 5 B-spline with knots every 6 months | Damping of the mean-square, second and third time derivatives of Br at the core-mantle boundary (CMB, at 3480 km radius) with enhanced damping of zonal terms up to degree 9. |
| Lithosphere | 120/120 | Static | Degree 19-120 purely determined by North-South differences from all satellites and East-West differences of lower pair satellite (A and C).  Damping of Br at Erath’s surface for degrees 91 and above to reduce noise |
| Ionosphere | 45/5 (quasi dipole coordinates) | Annual, semi-annual, 24-, 12-, 8- and 6- hours periodicity | Spherical harmonic expansion in quasi-dipole (QD) frame, underlying dipole SH *n*max = 60, *m*max = 12. Scaling by 3-months averages of F10.7 plus induction via a priori 3-D conductivity model (“1-D mantle + oceans”) and infinite conductor at CMB.  Regularisation of:   1. Mean-square current density J in the E‑region within the night-side sector (magnetic local times 21:00 through 05:00; peak damping at 01:00) 2. Mean-square of the surface Laplacian of J multiplied by a factor of sin8(2θ) over all local times, where θ is co-latitude. |
| Magnetosphere, external | 3/1 | One hour bins |  |
| Magnetosphere, induced | 3/3 | One hour bins |  |
| Toroidal | 45/5 (dipole coordinates) | Semi-annual and six hours periodicity | Meridional currents in QD frame, underlying dipole SH *n*max = 60, *m*max = 12, centred at 400 km altitude. |
| M2 Tidal | 18/18 | Periodicity: 12.42060122 hr, phase fixed with respect to 00:00:00, 1999 January 1 GMT |  |

Table 2‑1: Model Configuration

The data selection criteria are:

* Coarse agreement with CHAOS-6 field model: ΔB*c* ≤ 500 nT for all components *c=r,ϑ,φ*, and ΔF ≤ 100 nT.
* Kp ≤ 30 for gradient data, Kp ≤ 2- for field data
* Time-derivative of Dst: |dDst/dt| ≤ 3 nT/hour
* 30 second sampling period for satellite data, NS gradient data computed from 15 second differences
* core and tidal fields determined from night-side data only, i.e. with Sun ≥ 10° below the horizon

## Comments from Scientists in the Loop

### Derivation of Model

The final Comprehensive Inversion model using five years of Swarm data shows good agreement with alternative models and exhibits very good data residual statistics (Table 1‑3).

### Conclusion

The estimated model is assessed to be of good quality with very good agreement with the general structures of the ionospheric field.

1. Definitions of Tests
   1. Mean square vector field difference per spherical harmonic degree

The mean square vector field difference between models per spherical harmonic degree (*n*) is diagnostic of how closely the models match on average across the globe. The difference between Gauss coefficients of model *i* and model *j* can be defined as:

 Equation A‑1

where *n*  is the degree, *m* is the order, *a* is the magnetic reference spherical radius of 6371.2 km which is close to the mean Earth radius, and *r* is the radius of the sphere of interest, which is taken as r = a for comparisons at the Earth’s surface and r = 3480 km for comparisons at the core-mantle boundary.

Summing over degrees n from 1 to the truncation degree N and taking the square root yields the RMS vector field difference between the models *i* and *j* averaged over the spherical surface:

 Equation A‑2

* 1. Correlation per spherical harmonic degree

Analysis of spherical harmonic spectra is a powerful way to diagnose differences in amplitude between models but tells us little about how well they are correlated. The correlation per degree between two models again labelled by the indices *i* and *j* can be studied as a function of spherical harmonic degree using the quantity: 

 Equation A‑3

Ideally, the correlation should be close to 1 for all models, indicating that they have equivalent features and coefficients. If the correlation falls below 0.5, for degrees 1-9, then the models should be examined in more detail. Coefficients from degree 10-13 in IGRF and WMM are less well-determined (e.g. due to noise) and also change more rapidly so are not expected to be well correlated by the launch of the Swarm mission.

* 1. Visualisation of coefficient differences

A final method of visualising the differences in Gauss coefficients is to plot the differences as a triangular plot, with the zonal coefficients lying along the centre of the triangle, the sectorial coefficients along the edges and the tesseral coefficients filling the central regions. These plots will illustrate which, if any, coefficients are strongly divergent between models

* 1. Visualisation of spatial differences

A geographical investigation of the models can be made by plotting the differences in the Bx, By and B­z components of the field at radius r = a. Studying differences between the Swarm models and reference models in space yields insight into the geographical locations where disparities are located, illustrating whether biases or errors have arisen in certain regions (e.g. polar areas).

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* 1. Visualisation of spatial differences

A geographical investigation of the models can be made by plotting the differences in the Bx, By and B­z components of the field at radius r = a. Studying differences between the SWARM models and reference models in space yields insight into the geographical locations where disparities are located, illustrating whether biases or errors have arisen in certain regions (e.g. polar areas).