On the responses of thermospheric atomic oxygen to the 20-21 November 2003 superstorm

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Abstract

TIMED/GUVI limb measurements and TIEGCM simulations are used to investigate thermospheric atomic oxygen (O) responses on the z = -1.5 pressure surface (~160 km) to the 20 and 21 November 2003 superstorm. The comparison between GUVI data and TIEGCM predictions shows that they have good agreement during the storm.

A diagnostic analysis of TIEGCM results has been carried out to quantify the relative importance of the physical processes responsible for O storm-time changes.

- Horizontal and vertical advection, molecular diffusion are the three main processes driving storm-induced O perturbations in the thermosphere.
- Horizontal and vertical advection dominate O changes at high latitudes in storm initial and main phases. Horizontal advection plays a significant role in global O perturbations over the entire course of the storm, including the recovery phase.
- Molecular diffusion acts to compensate for the O perturbations caused by horizontal and vertical advection.

1. Introduction

O is an important species in the thermosphere, and is a challenging species to measure and model due to its highly reactive and variable nature.

Previous studies pay less attention to O perturbations during major geomagnetic storms due to lack of observations.

GUVI and GOLD disk-viewing measurements provide $\sum O/N_2$ data with high temporal and spatial distributions, $\sum O/N_2$ gives thermospheric neutral composition information around 140-180 km.

Here we use O number density on the z = -1.5 (~160 km) pressure surface derived from GUVI limb measurements and TIEGCM simulations to investigate storm-time changes of O and the physical mechanisms driving these changes.

2. Data and Method

Data source : GUVI limb neutral density profiles; Level 2B version 13 (110 -667 km)

TIEGCM : A time-dependent, three-dimensional global model (~97 - 600 km)
Horizontal resolution : 1.25°× 1.25° (Ψ_o is the O mass mixing ratio)

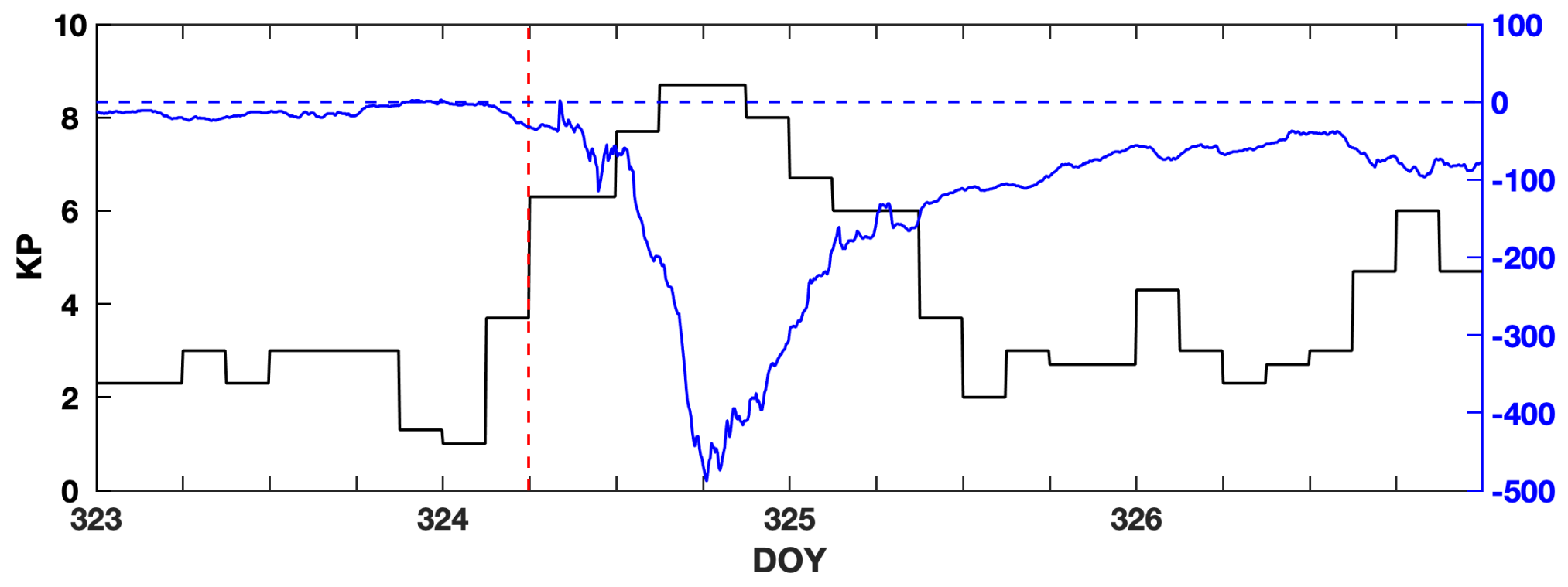
$$\frac{\partial \boldsymbol{\Psi}_\mathbf{o}}{\partial t} = -\frac{e^z}{\tau}\frac{\partial}{\partial z}\left[\frac{\bar{m}}{m_{N_2}}\left(\frac{T_{00}}{T_n}\right)^{0.25}\boldsymbol{\alpha}^{-1}\mathbf{L}\boldsymbol{\Psi}_\mathbf{o}\right] + e^z\frac{\partial}{\partial z}\left[K(z)e^{-z}\frac{\partial}{\partial z}\boldsymbol{\Psi}_\mathbf{o}\right] - (\mathbf{V}\cdot\nabla\boldsymbol{\Psi}_\mathbf{o}) - \omega\frac{\partial \boldsymbol{\Psi}_\mathbf{o}}{\partial z} + S - R \Rightarrow$$

Molecular diffusion
Eddy diffusion
Horizontal advection
Vertical advection
Production
Loss.

⇩

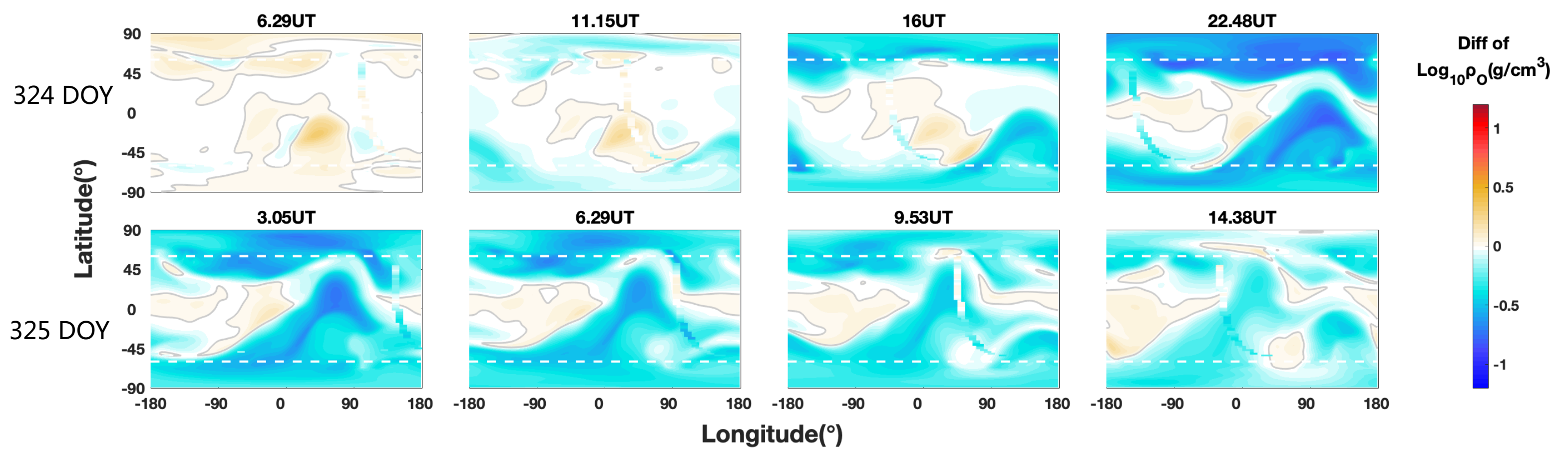
Comparing the magnitude and distribution of Ψ_o, $\frac{\partial \boldsymbol{\Psi}_\mathbf{o}}{\partial t}$ and each term, we can understand the relative importance of the main physical mechanisms to the storm-time O variations.

Figure 1. 3-hr Kp and hourly Dst indices on DOY 323-326 in 2003.



3.1 Data/Model Comparison

Figure 2. O mass density differences along GUVI orbits (data) and predicted by TIMGCM



- Model results are consistent with the GUVI observations.
- Large O depletion first occurred at high altitudes on the nightside and in the longitude sector adjacent to the magnetic pole.
- A bulge of ρ_O depletion in the SH extended into the NH near the storm peak. The equatorward extension of NH O perturbations was relatively weak. The O perturbation region has a tendency of westward movement.
- Most of the physical processes of storm-time O perturbations are reasonably represented in the TIEGCM.

3.2 Physical Mechanisms of O Responses to Storm

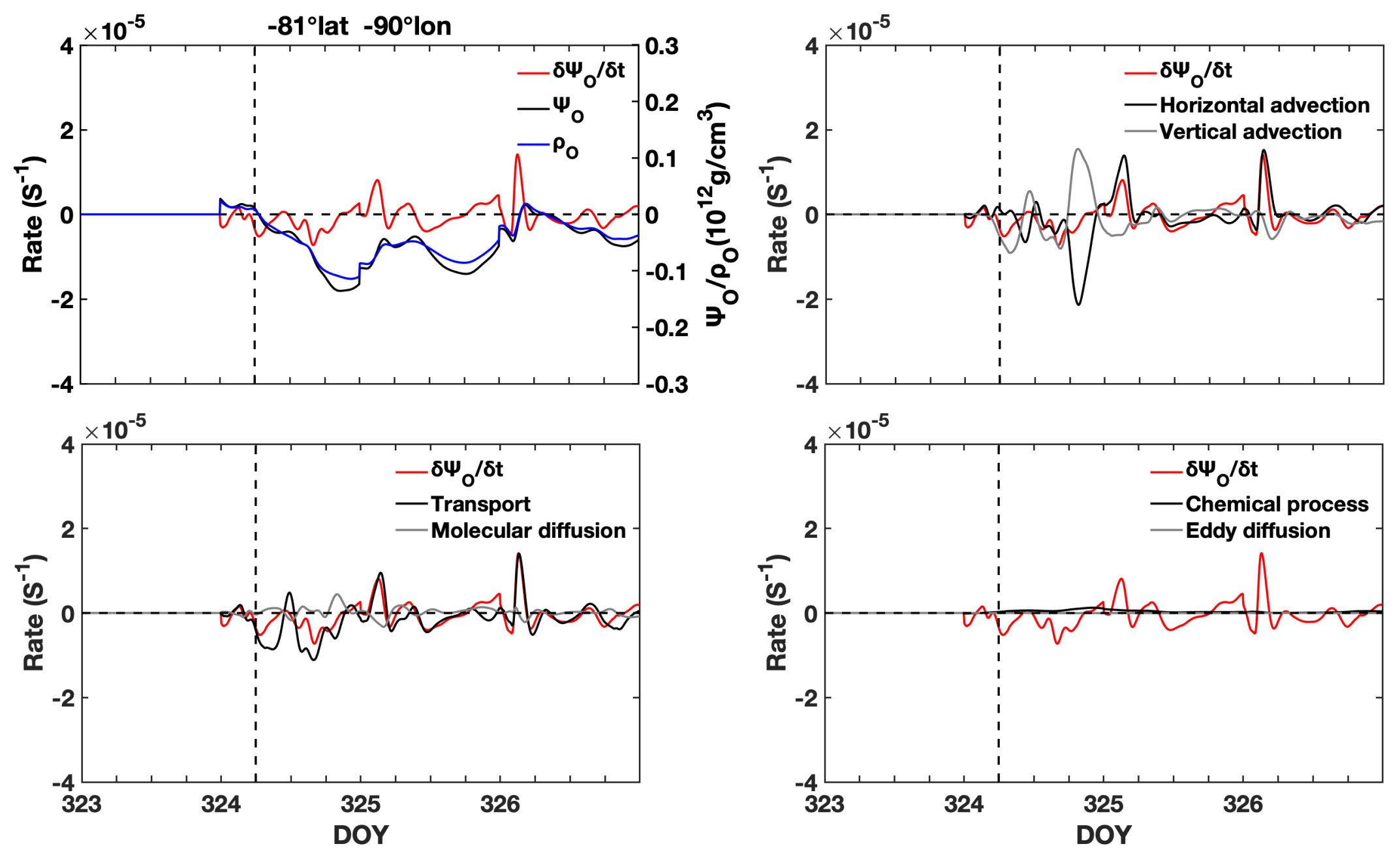
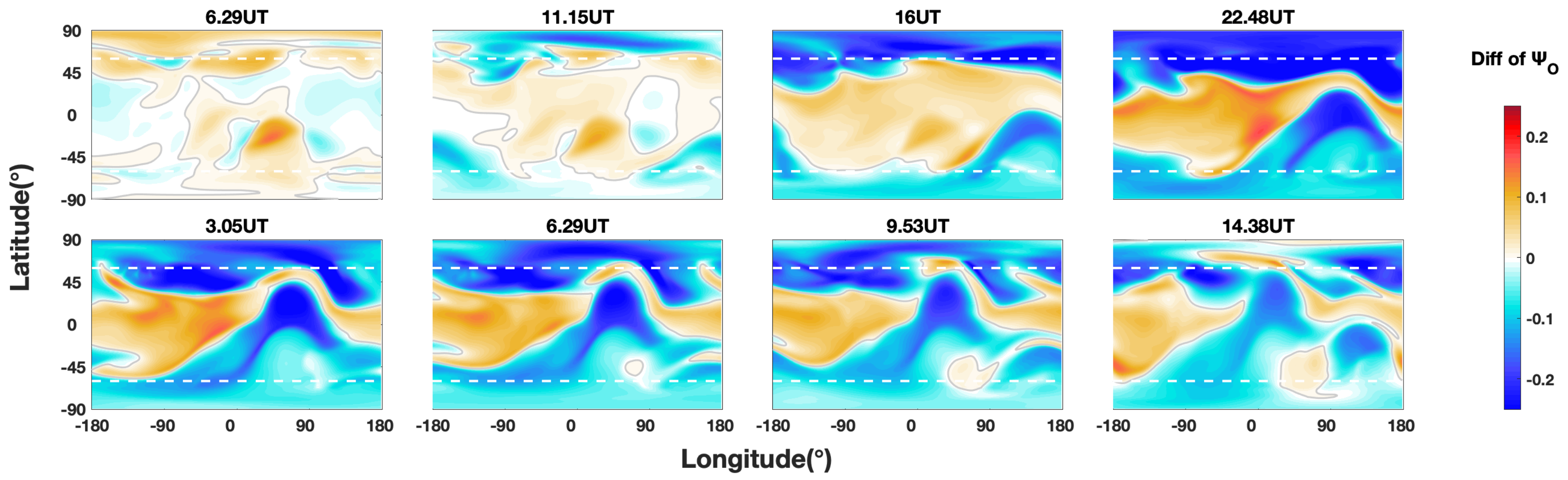


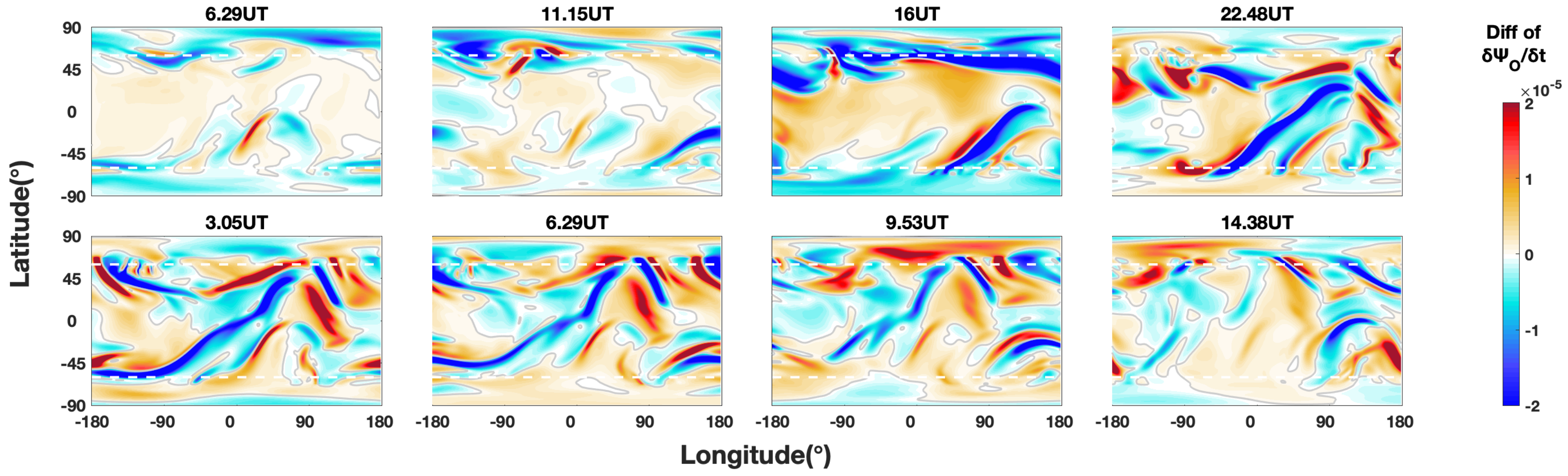
Figure 3. Variations of Ψ_o, ρ_O, $\partial\Psi_o/\partial t$, and all terms at 81°S, 90°W

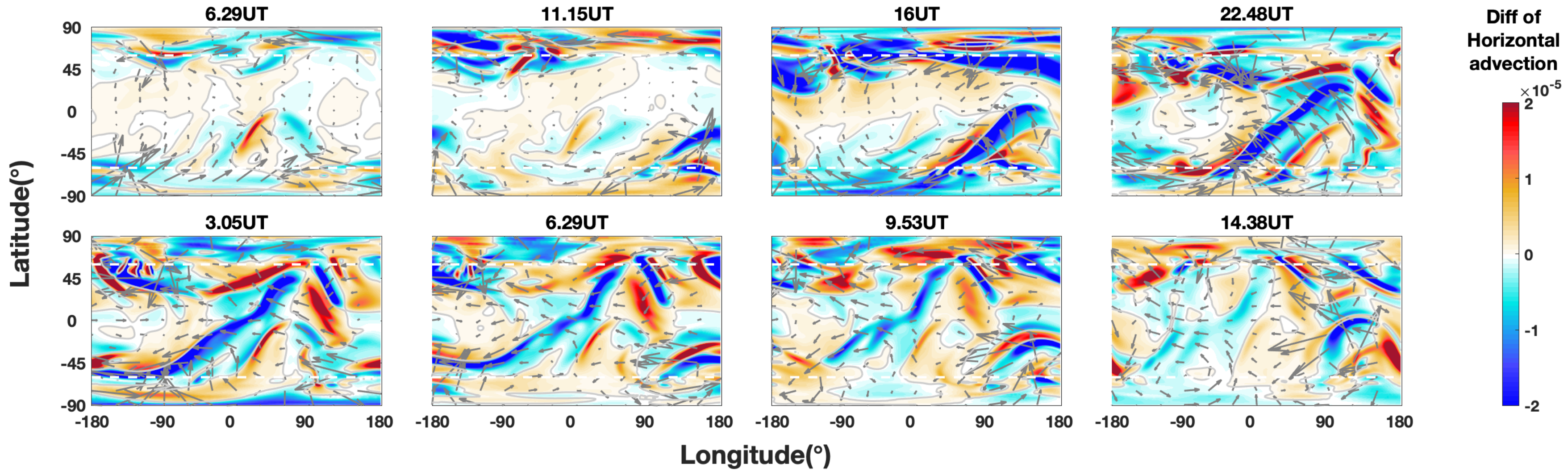
- Ψ_o and ρ_O perturbations are consistent.
- Ψ_o responses are a time-integrated effect of all the terms.
- At the storm onset, the dominant compositional forcing term in the auroral oval is vertical advection
- Transport by advection dominates the storm-time variation of Ψ_o.
- Molecular diffusion has a tendency to balance the transport effect.
- Chemical process and eddy diffusion are negligible on this pressure level.

Figure 4. Global maps of Ψ_o, $\partial\Psi_o/\partial t$, horizontal advection, vertical advection, molecular diffusion changes (storm-quite) on the z=-1.5 (~ 160 km) pressure surface.

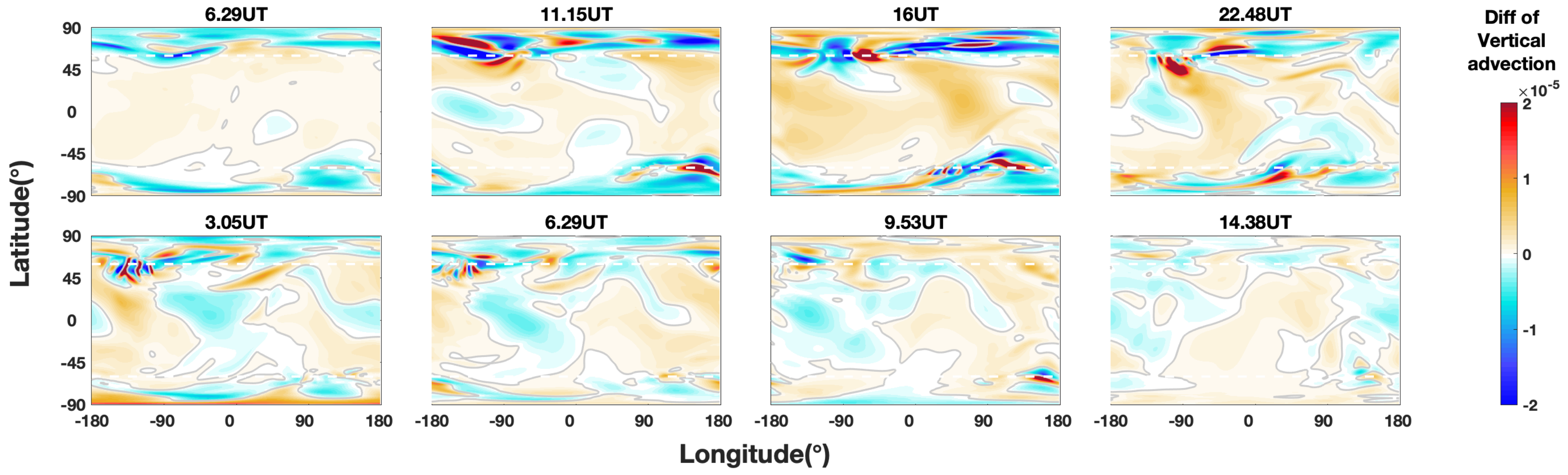


Storm-time changes of Ψ_o are consistent with those of ρ_O shown in Figure 2

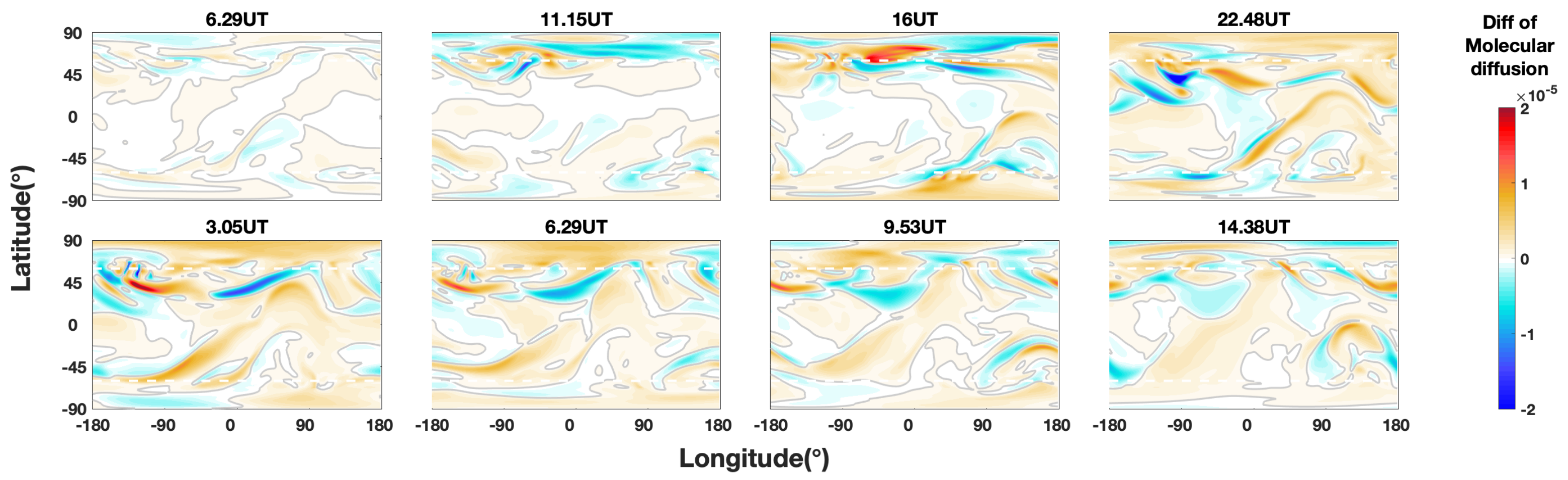




- Horizontal advection is driven by horizontal neutral winds and strong gradients in Ψ_o.
- Storm-time Horizontal winds blow from high latitudes to low latitudes in both hemispheres, as well westward due to the Coriolis force.



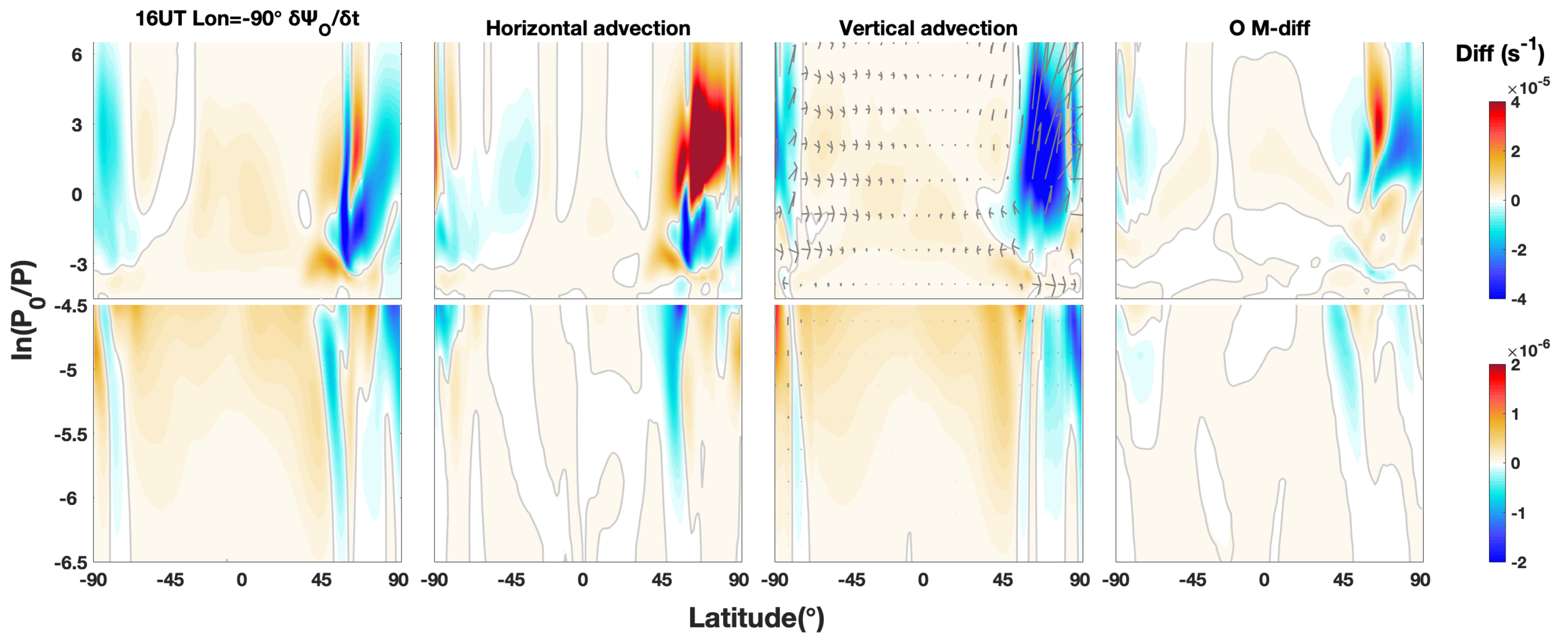
- During the storm initial and main phases, horizontal and vertical advection dominates the total rate of change of Ψ_o at high latitudes. At middle and low latitudes horizontal advection is the main driver for Ψ_o change, vertical advection is also important.
- During the recovery phase, horizontal advection is the dominant process for Ψ_o changes globally.



Molecular diffusion is relatively small globally, compared with the other two terms. The effect of molecular diffusion is opposite to that of the advection, acting to compensate for the Ψ_o changes caused by horizontal and vertical advection.

4 Discussion

Figure 5. Altitude-latitude differences (storm-quiet) of $\partial\Psi_o/\partial t$, horizontal advection, vertical advection superimposed with neutral winds, and molecular diffusion in pressure coordinates at 90°W for 16 UT.



High latitude O perturbations on z = -1.5 pressure level are the result of upwelling. O perturbations were transmitted to lower latitudes by neutral wind advection.

5. Conclusion

To conclude, TIEGCM can simulate reasonably well the storm-induced perturbations of O density when comparing with GUVI measurements. Diagnostic analysis of model results has been performed to determine quantitatively the physical mechanisms responsible for O perturbations during the superstorm.

- O perturbations are the time-integrated effect of all the terms. Horizontal advection, vertical advection and molecular diffusion are the three main processes driving O perturbations from the onset to the recovery of the superstorm on the z = -1.5 pressure level. Chemical process and eddy diffusion play a very minor role.
- The O perturbations are caused mainly by horizontal and vertical advection during the storm initial and main phases. During the recovery phase, the global O perturbations are mostly driven by horizontal advection.
- The sign of the molecular diffusion term is opposite to that of $\partial\Psi_o/\partial t$, acting to compensate for the O changes caused by horizontal and vertical advection.
- The altitude-latitude maps show that O perturbations of high latitudes on z = -1.5 pressure level are driven by the upwelling, and were transported to mid-low latitudes by the neutral winds. In addition, at mid-high latitudes of NH, molecular diffusion plays an important role at above z = 0 (~220 km).

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