Short-term variability and the weather of the day in the lower thermosphere and ionosphere using a whole atmosphere model with upper atmospheric observations

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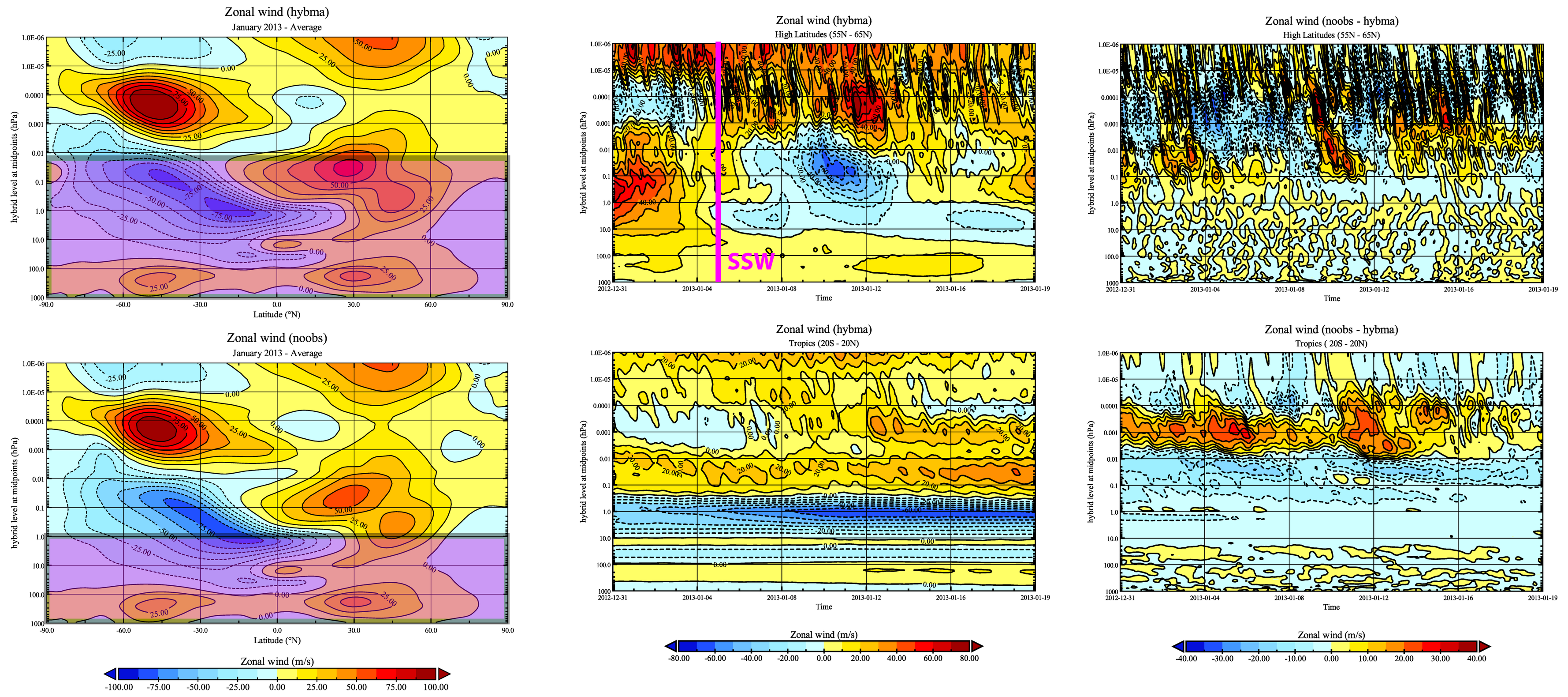
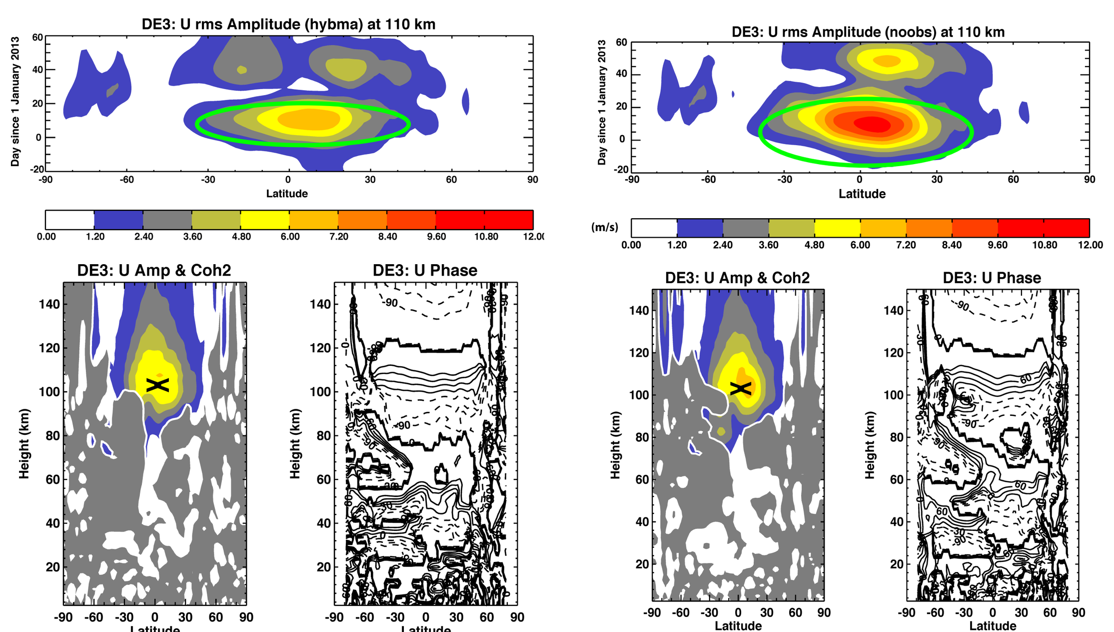
Abstract. Whole atmosphere models that fully capture the propagation of wave dynamics from lower to upper atmosphere are believed to be sufficient to reproduce the type of short-term variability in the neutral upper atmosphere that produces observed variations in ionospheric parameters. However, recent studies suggest that upper atmospheric observations are needed to accurately represent short-term variability in both planetary-scale mass transport and tidal behavior crucial to representing the structure of the thermosphere and the wind-dynamo coupling in the ionosphere. To address this, we use atmospheric specifications from the prototype High-Altitude Navy Global Environmental Model (NAVGEM-HA) from the ground to 92 km to nudge the Whole Atmosphere Community Climate Model extended version (WACCM-X) coupled to the NRL SAMI3 (Sami is Another Model of the Ionosphere) via the coupling layer of the Navy Highly Integrated Thermosphere Ionosphere Demonstration System (Navy-HITIDES). The HA-NAVGEM data assimilation/forecast system is run in two configurations: a reference experiment for the time period December 2012-March 2013, where satellite-based middle atmospheric observations (SABER temperature retrievals; Aura MLS temperature, ozone, and water vapor retrievals; and SSMIS microwave radiances) are included between 20-90 km (hereafter **hybma**); and a perturbed experiment, during the same time period, in which the middle atmospheric observations are removed (hereafter **noobs**). The resulting nudged simulations using WACCM-X coupled to SAMI3 are used to study the impact of upper atmospheric observations in reproducing the observed short-term variability in the thermosphere-ionosphere system, both in terms of the thermospheric structure and the ionospheric response via wind-dynamo coupling. Here, we discuss the role of solar thermal non-migrating (DE3) and lunar gravitational migrating (M2) tides.



hybma: SD-WACCM-X + NAVGEM-HA with obs from ground to 90 km
noobs: SD-WACCM-X + NAVGEM-HA with obs from ground to ~50 km
The hybma- and noobs-SD-WACCM-X simulations are identical below 1 hPa (~50 km), but they start to diverge in the mesosphere and are quite different in the thermosphere. The reason for such differences can be several: at midle and high latitudes, the GWD parameterization impacts directly the zonal wind character; at tropical latitudes, indirect effects of the GWD via the mean meridional circulation and differences in tropically bounded waves can also be important.

Non-Migrating Solar Diurnal Tide DE3



DE3 amplitude is about 2x in noobs w.r.t. hybma.

It is interesting that the most marked differences in DE3 amplitude occur at the time of a SSW.

The ***tropical winds*** in the upper mesosphere are more westward in noobs but given the phase velocity of DE3 (c~150 m/s) it is unlikely that filtering from the background winds is responsible for the DE3 amplitude difference.

The ***tropical waveguide*** is slightly wider in noobs compared to hybma (not shown), suggesting only a modest impact of the wind shear on the tidal amplitude.

Is it possible that wave-wave non-linear interactions are sufficiently different to explain the different tidal amplitude?

We need to define a covariance that is function of frequency and time. We thus exploit the properties of the S-transform:

Be $S(\tau,f)$ is the S-transform of field h(t):

$$S(\tau,f)=\int_{-\infty}^{+\infty} h(t)\frac{|f|}{\sqrt{2\pi}}e^{\frac{-(\tau-t)^2 f^2}{2}}e^{-i2\pi f t}dt \qquad (1)$$

(see Stockwell et al., 1996 – hereafter S96). For any given spectral band, I define the spectral band average of (1) as:

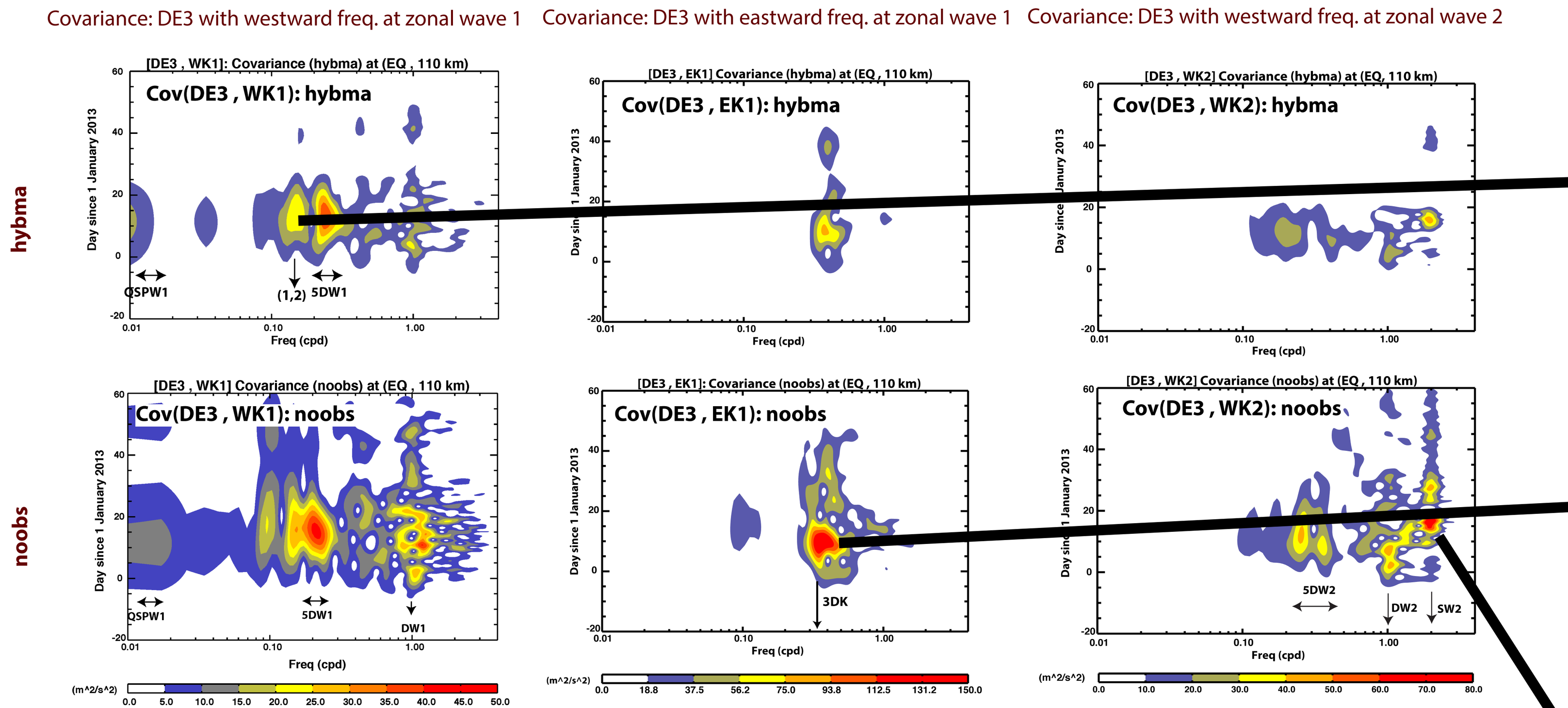
$$\langle S(\tau)\rangle_{f_0}=\sum_{i=-N_f/2}^{+N_f/2} S(\tau,f_i)e^{i2\pi f_i\tau} \qquad (2)$$

where $f_i = [f_0-\Delta f*N_f/2, \ldots, f_0, \ldots, f_0+\Delta f*i, \ldots f_0+\Delta f*N_f/2]$. In the limit of $N_f \rightarrow \infty$, and with summation replaced by an integral, then (2) reduces to Eq. (6) in S96, and the full temporal behavior of *h(t)* is recovered. Thus, (2) represents the limiting behavior in the spectral band around f_0.

The covariance follows naturally from (2) using standard definitions; the covariance between the averaged complex behavior in spectral band f_0 w.r.t. any other complex behavior at frequency f_k is simply:

$$Cov(S_0,S_k)=\left(\langle S(\tau)\rangle_{f_0}\right)S(\tau,f_k) \qquad (3)$$

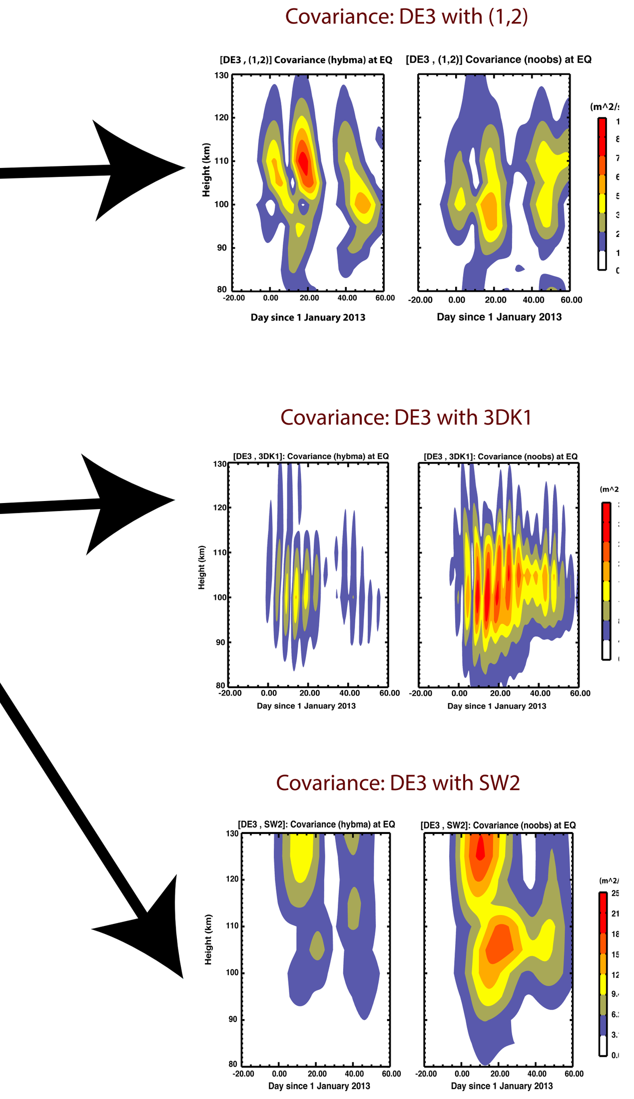
Covariance: DE3 with westward freq. at zonal wave 1 — Covariance: DE3 with eastward freq. at zonal wave 1 — Covariance: DE3 with westward freq. at zonal wave 2

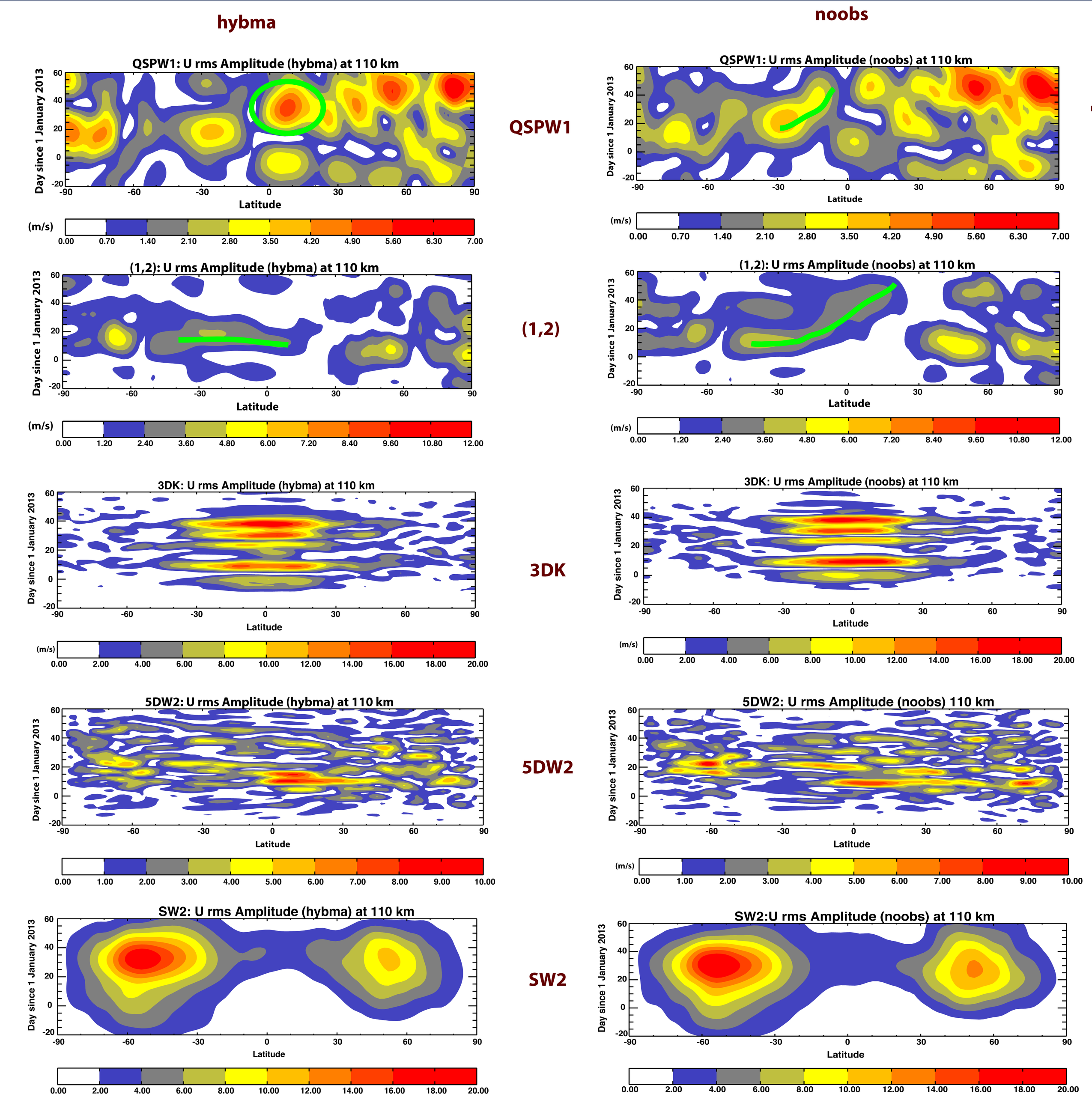


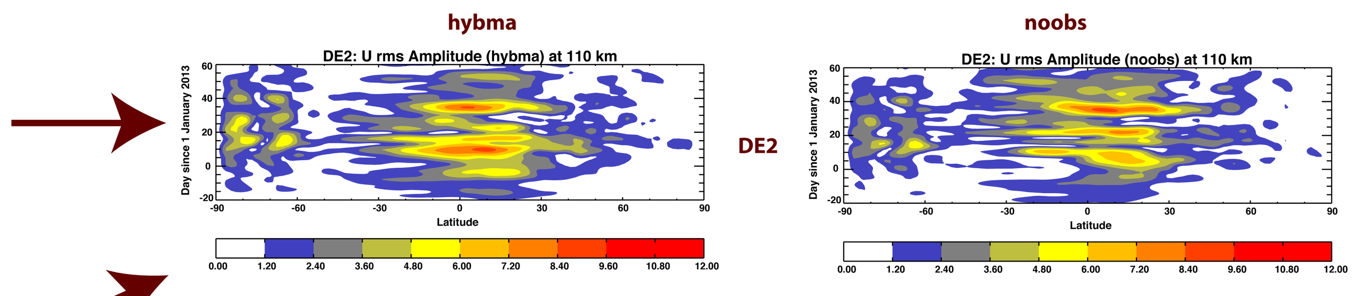
DE3 + QSPW1 (or, [1,2]) ~ --> DE4
DE3 - QSPW1 (or, [1,2]) ~ --> DE2
DE3 + 5DW1 --> (k=4 , f= E0.8 cpd)
DE3 - 5DW1 --> (k=2 , f= W1.2 cpd)

DE3 + 3DK1 --> (k=4 , f= E1.3 cpd)
DE3 - 3DK1 --> (k=2 , f= E0.7 cpd)

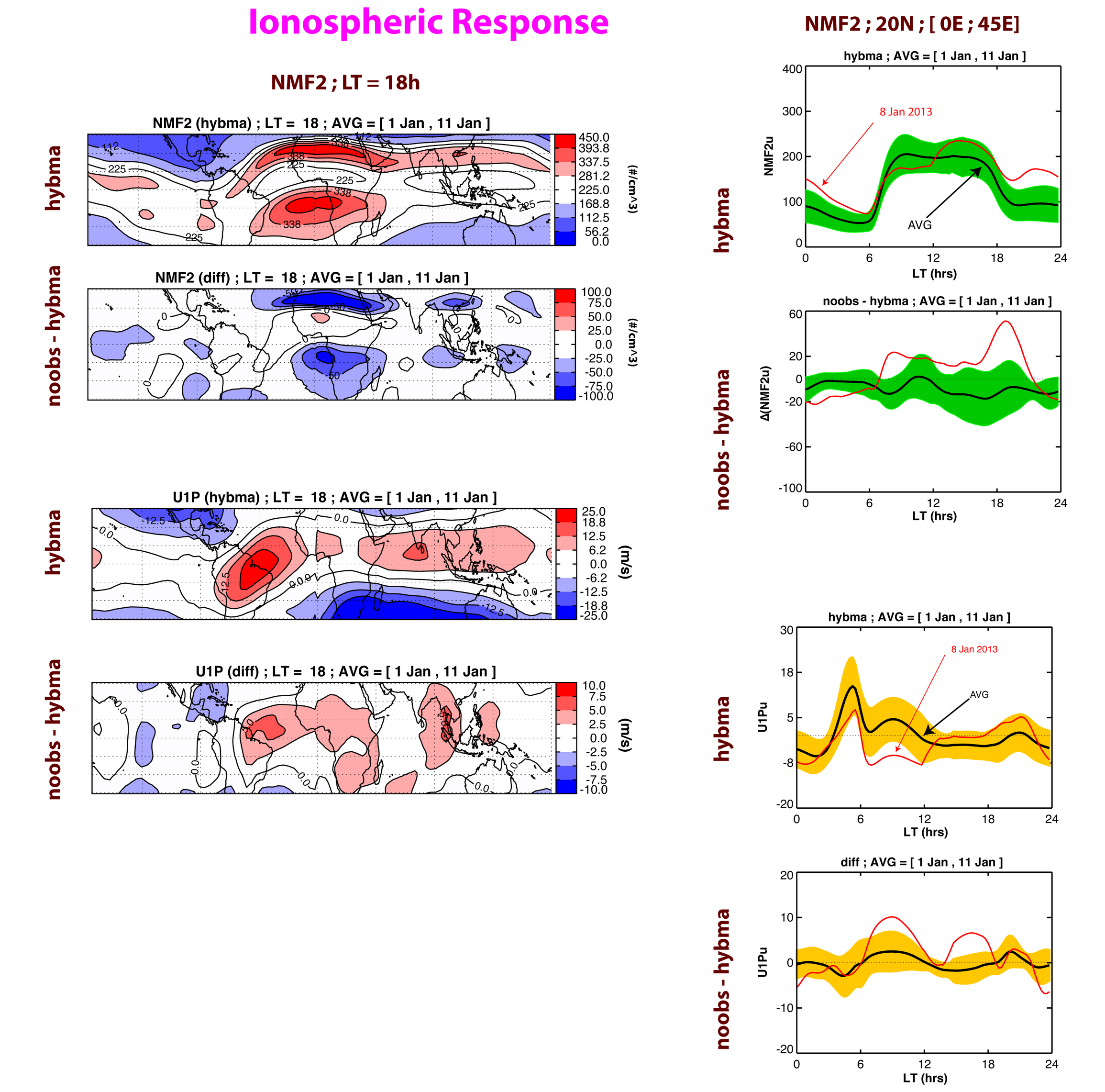
DE3 + SW2 --> DW5
DE3 - SW2 --> TE1
DE3 + DW2 --> SPW(E)5
DE3- DW2 --> SE1
DE3 + 5DW2 --> (k=5 , f= E0.8 cpd)
DE3 - 5DW2 --> (k=1 , f= E1.2 cpd)



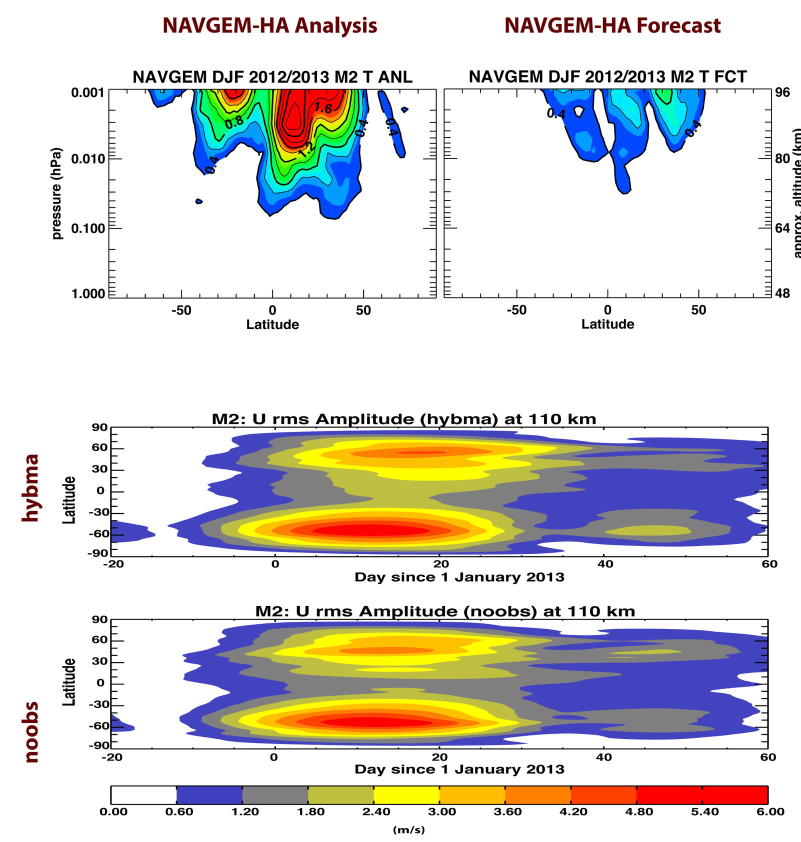




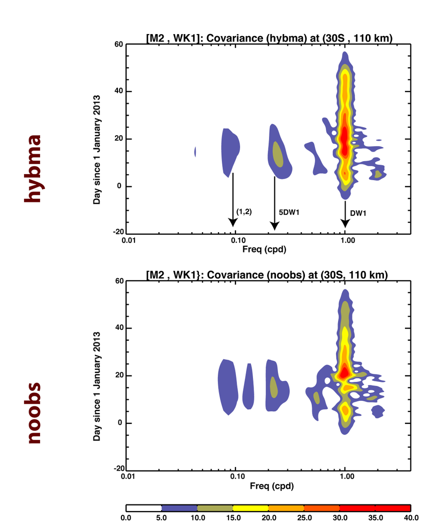
Ionospheric Response



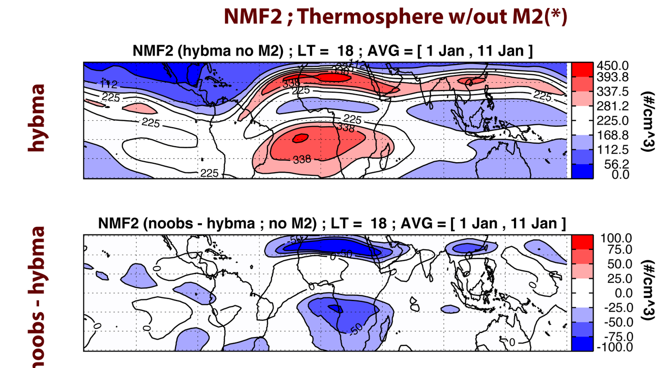
Semidiurnal Lunar Tide (M2)



Covariance M2 with WK1

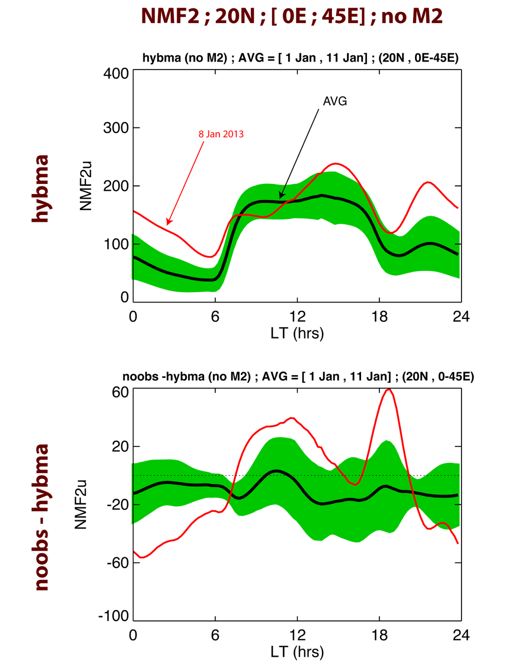


NMF2 ; Thermosphere w/out M2(*)



(*) **M2** is removed spectrally via a Fourier analysis from the neutral meteorology that drives the ionosphere. Non-linear effects due to wave-wave interactions that occur in the whole atmosphere model are not affected.

NMF2 ; 20N ; [0E ; 45E] ; no M2



Conclusions. We determined that upper atmospheric observations are crucial for the description of the state of the thermosphere. Without upper atmosphere observations, the amplitude of some non-migrating tides (prominently **DE3**) is substabtially different (2x **noobs** vs. **hybma**) due to non-linear interactions with normal modes (such as the [1,2] Rossby 10-day wave) in the upper atmosphere. These modes are forced more efficiently in the **hybma** simulation and interact non-linearly with the DE3 tide, removing energy from DE3 and resulting in children waves which add variability in a spectral range approximately corresponding to the DE2 non-migrating tide. Our results show also that such interaction between DE3 and (1,2) is not exclusive; DE3 is shown to interact also with fast Kelvin waves and with migrating DW1 and SW2 tides. The ultimate impact on the ionosphere is a marked reduction of the wave-3/4 structure in NMF2 during the times of wave-wave interactions. It is also noted that the behavior of the ionosphere around the time of the January 2013 SSW is different, depending on the presence (or not) of upper atmospheric observations.

We also compared **hybma** and **noobs** simulations in the spectral band of the lunar semidiurnal tide **M2**. We show that the M2 tide is present in the NAVGEM-HA analysis, but its amplitude is much reduced in the forecasts, illustrating how M2 is forced by the data assimilation, and there is no physics to force M2 in the unconstrained forecasts. The space-time structures of M2 in the two simulations are broadly similar, indicating that M2 is forced by lower atmosphere data and the presence (or not) of upper atmospheric observations is not crucial for this tide. However, we show that M2 can also interact non-linearly with numerous solar tides and normal modes in the lower thermosphere, especially DW1 and Rossby (1,2) and (1,3) modes. Such interactions are only modestly simulation-dependent when M2 is removed linearly from the driving meteorology of the thermosphere. While this procedure does not remove non-linear interctions already present in the thermospheric fields, such experiment illustrates that the linear nature of M2 impact appears to be very similar with and w/out upper atmospheric observations in the mean ionospheric response. However, intra-day differences show a more marked semi-diurnal impact in the simulations w/out M2.

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