IRENE Solar Cycle Variation

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Motivation/Questions/Issues

- IRENE users have requested solar cycle variation for low-altitude protons
- Fluxes at low altitudes are controlled by atmosphere as well as magnetic field
- Will require modifications to IRENE processing and software
  - Need to be able to map measurements to a “reference state” and then transform back when the model is queried
  - We will have to apply the transformation to all data currently processed
- How realistic does the model need to be?
  - How will users use it?
  - Variations of about a factor of 10 are observed, but in regions of low flux
- How to handle future solar cycles
  - Prediction of solar cycle more than a few years in the future (especially multiple solar cycles) is highly uncertain
  - Use an “average” solar cycle? Or a “quiet” one (to be conservative)? What is “quiet”?
  - Note Paul O’Brien’s solar cycle ($F_{10.7}$) model

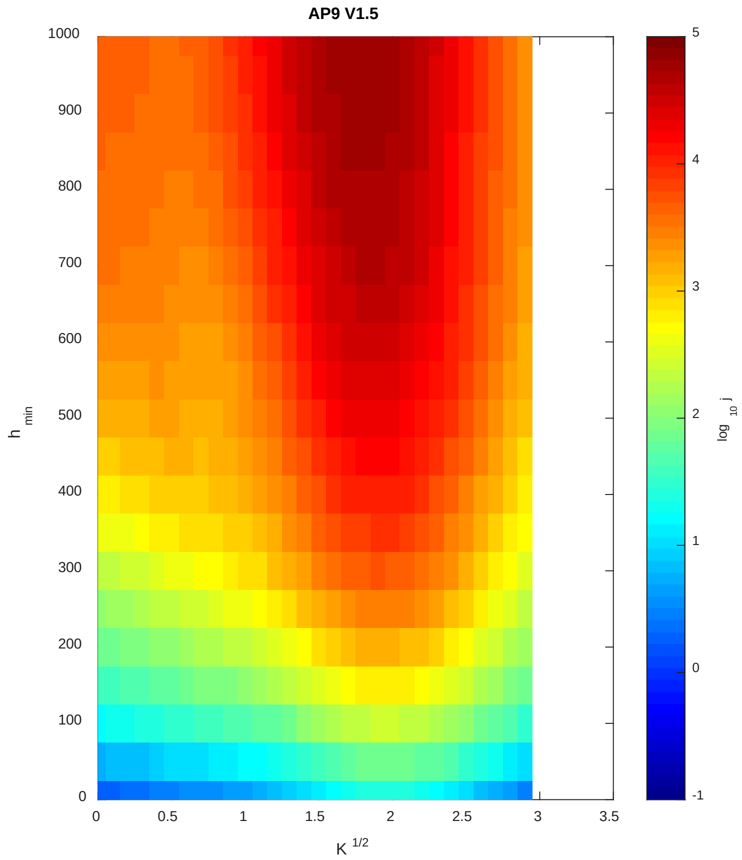
Motivation/Questions/Issues

- How will adding cycle variations affect the flux maps and software?
  - Maps currently contain the solar cycle variation implicitly
  - What does the new model mean for propagation over time?
- Solar minimum (flux maximum) occurs at different times for different energies, locations
- Solar minima are about the same in terms of $F_{10.7}$
  - This means that modeled fluxes will be about the same for all solar minima
- Spectral shape changes from solar min to solar max

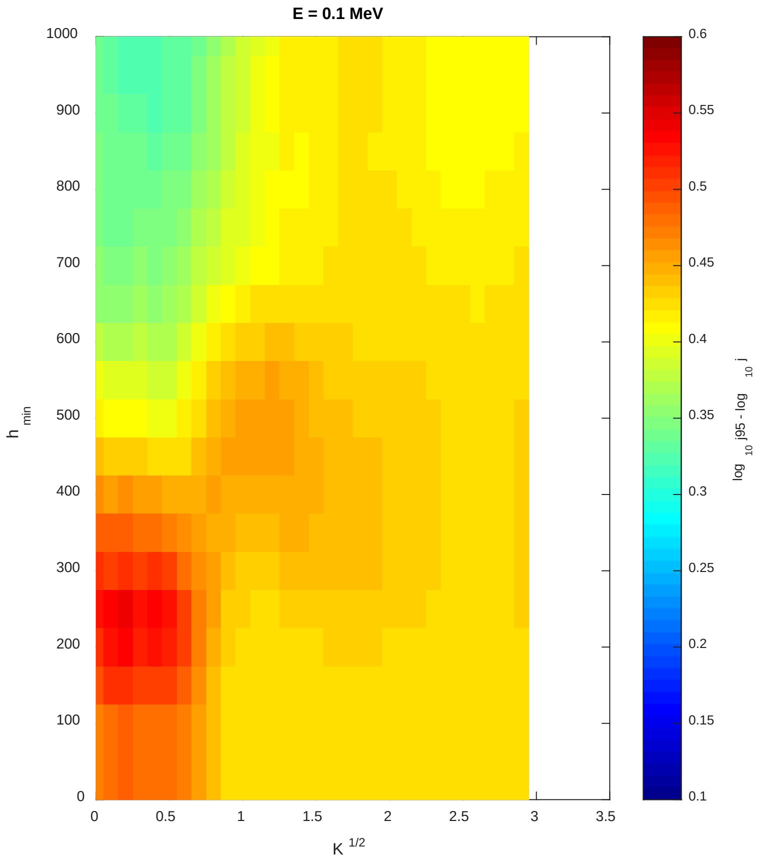
Requirements

- All energies 0.1 – 2000 MeV
- $0 \leq K^{1/2} \leq 3$; Range of K decreases with increasing energy
- $0 \leq h_{min} \leq 1000$ km
- Needs to be computationally efficient

AP9 Flux Maps 0.1 MeV



$\log10(j_{mean})$



$\log10(j_{95}/j_{mean})$

- Left panel shows flux map -- $\log_{10}(j_{mean})$
- Right panel shows variance within bins -- $\log10(j_{95}/j_{mean})$
- Note maps only go out to $K^{1/2} = 3$

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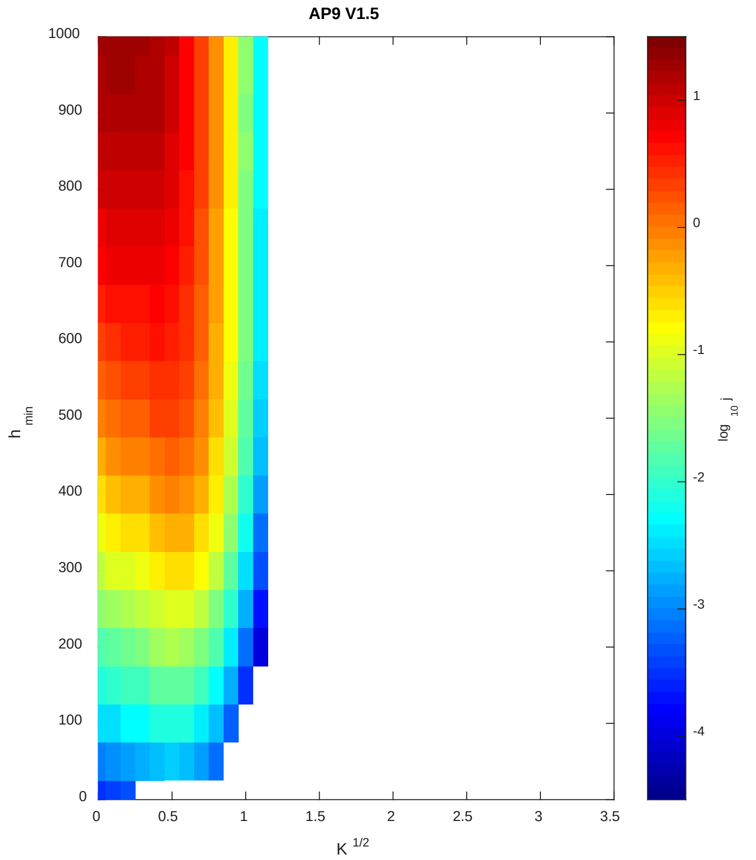
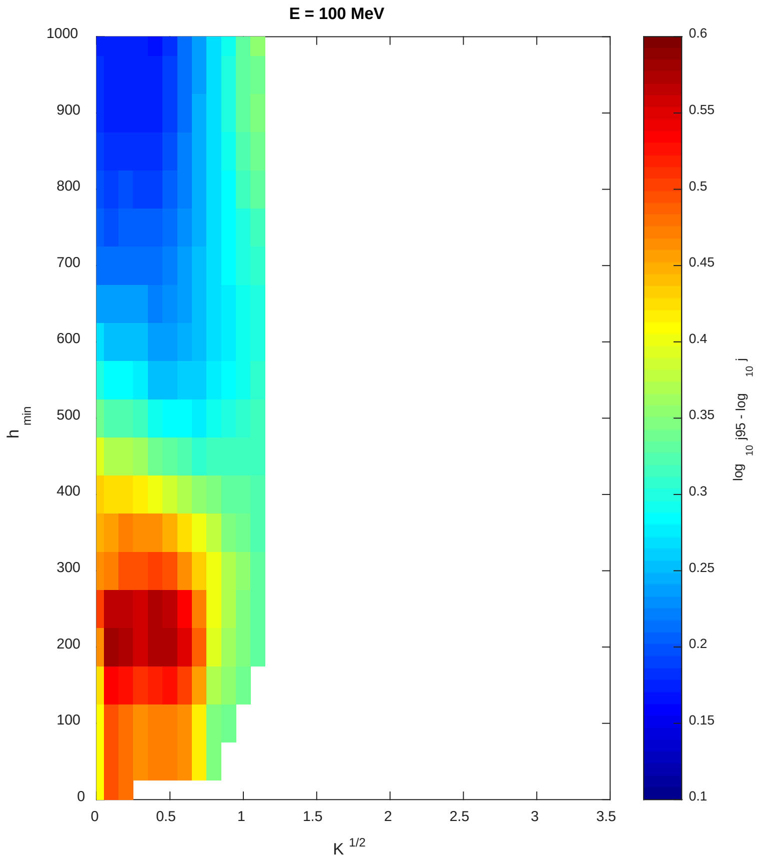
AP9 Flux Maps 100 MeV





$\log10(j_{mean})$ $\log10(j_{95}/j_{mean})$

- Left panel shows flux map -- $\log_{10}(j_{mean})$
- Right panel shows variance within bins -- $\log10(j_{95}/j_{mean})$
- Range of $K^{1/2}$ is much smaller

Notional Procedure

- Simple correlation based on phase-lagged $F_{10.7}$ (as in NOAAPRO and TPM-1):

$$\phi(t) = \phi_0 \exp\left(-\frac{F_{10.7}(t-\tau)}{F_0} \right)$$

- Parameters Φ_0, F_0, and τ are functions of E, K, and h_{min}. (Φ_0 is not really used – it will be determined from the individual data sets)
  - τ is a phase lag
  - F_0 is a modulation parameter – smaller values imply larger modulation
- Parameters can be derived from Selesnick Inner Zone Proton Model (SIZM) or spectral inversion of POES data or other models/data, e.g., SAMPEX
- Using the correlation, transform fluxes measured at a given time back to a “reference solar minimum” for inclusion in flux maps
- To obtain model flux at a given solar cycle state, use the correlation to transform back

Sources of Data

SIZM

- Convert from M/K/L* to E/K/h_{min}
- 1969 – 2005 (3-1/2 solar cycles)
- E: 6 – 2000 MeV
- $K^{1/2}$: 0 – 1.5
- h_{min}: 0 – 2500 km

POES

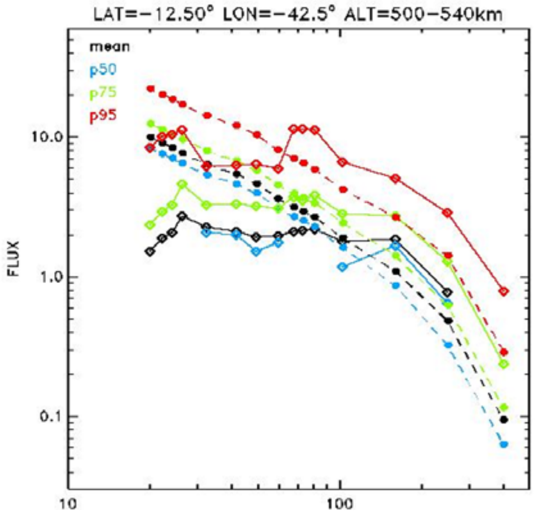
- Spectral inversion of POES SEM-2
- 1998 – 2015 (1-1/2 solar cycles)
- E: 16 – 300 MeV
- $K^{1/2}$: 0 – 0.7
- h_{min}: 0 – 800 km

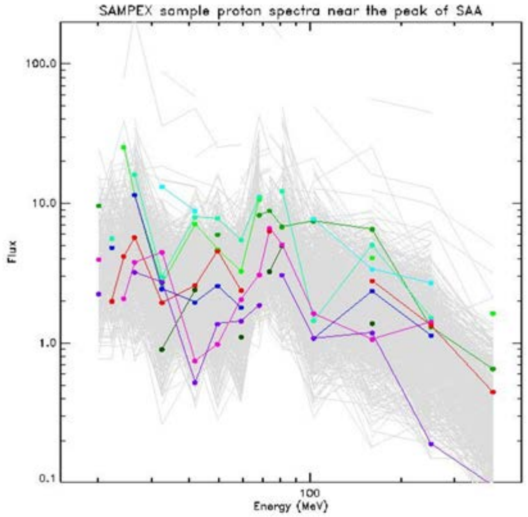
Comments on POES

- Spectral inversion depends on assumptions about
  - Response functions
  - PC spectral model
  - Pitch angle distributions
- Spectral shape below 30 MeV is especially uncertain
- While absolute calibration of inverted fluxes is questionable, variations over the solar cycle should be fairly consistent
- SEM-1 could also be used, but > 16 MeV channel is subject to electron contamination
  - Would extend the data base to ~ 40 years
  - Would require inversions

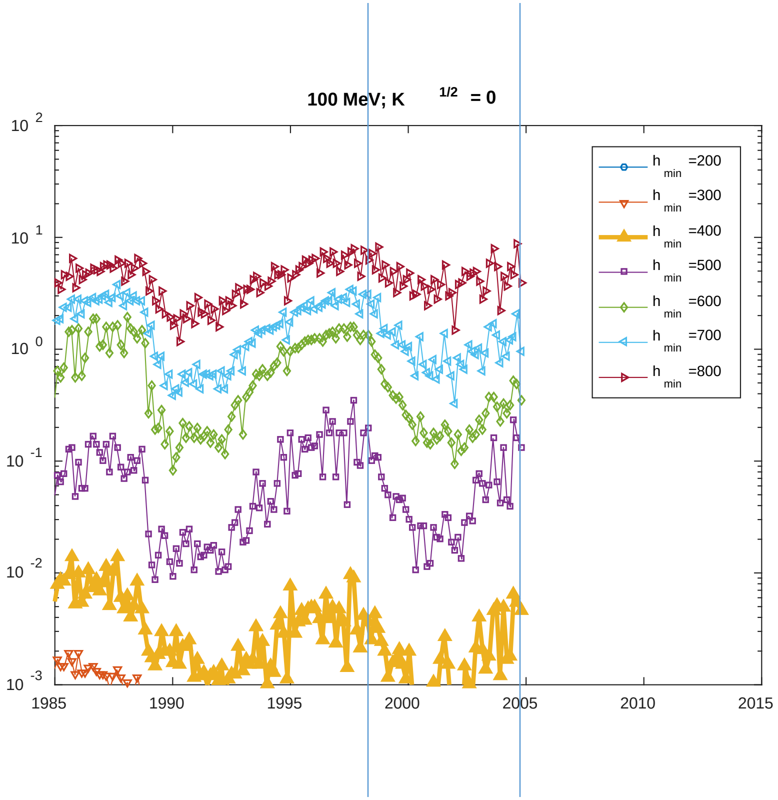
Comments on SAMPEX/PET

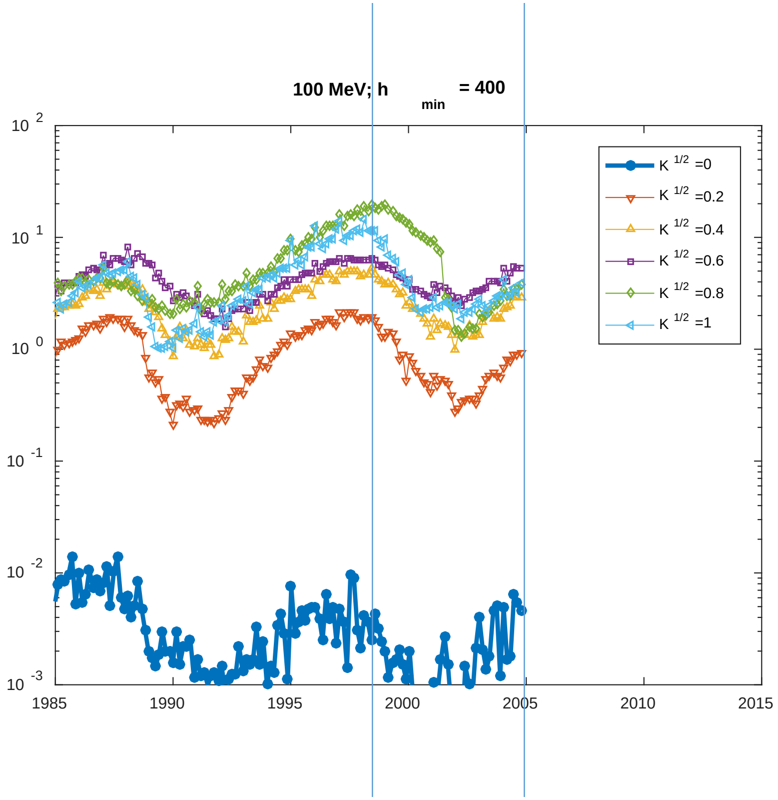
- SAMPEX was not used for this study, but would be a good source of data
- 1992 – 2009 (1-1/2 solar cycles) – Reentry in 2012
- E: 19 – 500 MeV
- $K^{1/2}$: 0 – 1 (?)
- h_{min}: 0 – 550 km
- Daniel Heynderickx has processed data from 1992 - 2009
- There are issues with individual/average spectra (right)
- Mark Looper has discussed needed improvements – latest info is from Oct. 2017



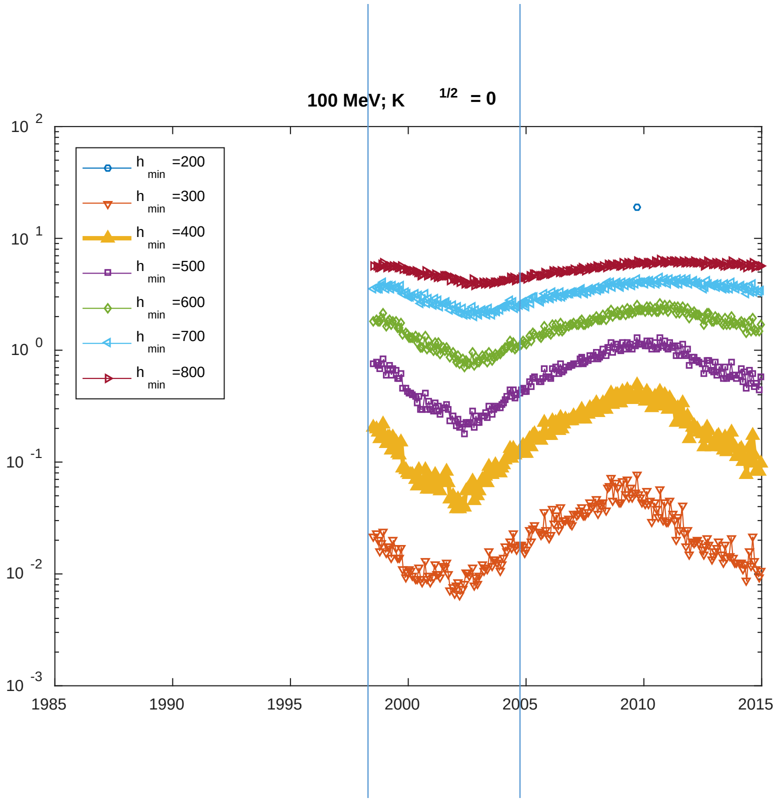


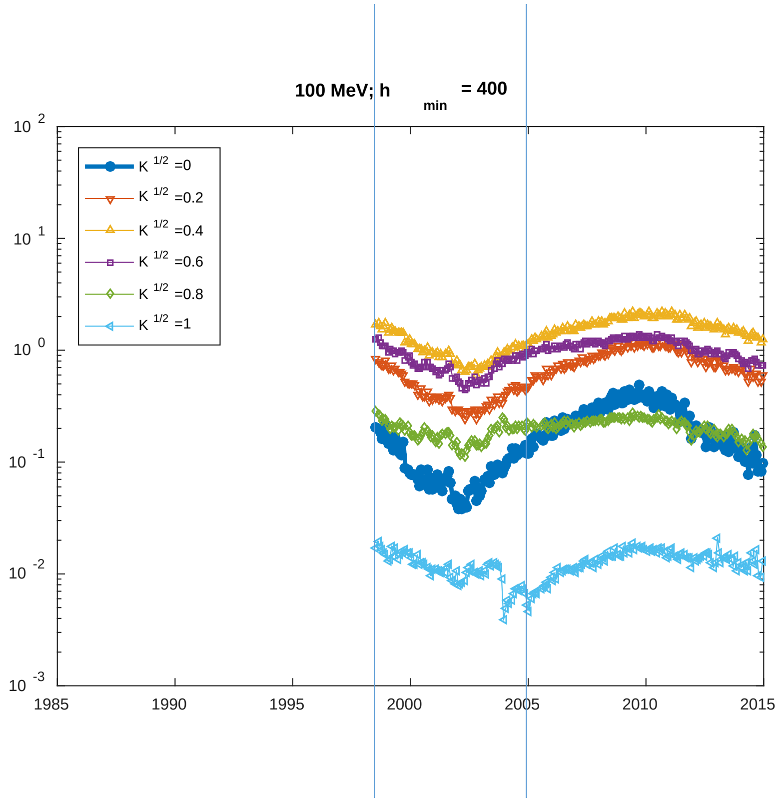
Temporal Variations: SIZM





POES


100 MeV; K 1/2 = 0
h min =200
h min =300
h min =400
h min =500
h min =600
h min =700
h min =800
10 2
10 1
10 0
10 -1
10 -2
10 -3
1985
1990
1995
2000
2005
2010
2015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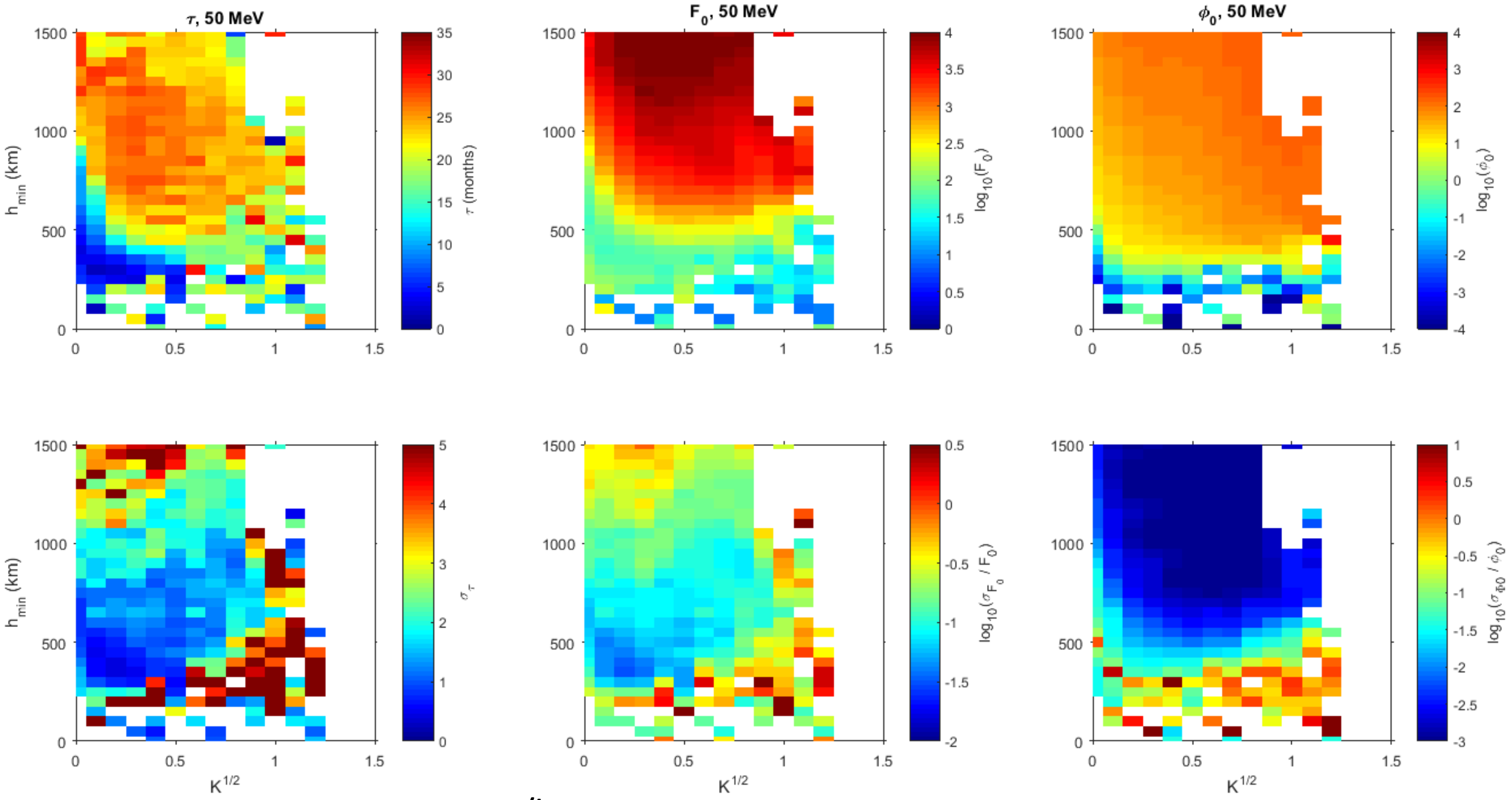
K 1/2 =0
K 1/2 =0.2
K 1/2 =0.4
K 1/2 =0.6
K 1/2 =0.8
K 1/2 =1
10 2
10 1
10 0
10 -1
10 -2
10 -3
1985
1990
1995
2000
2005
2010
2015

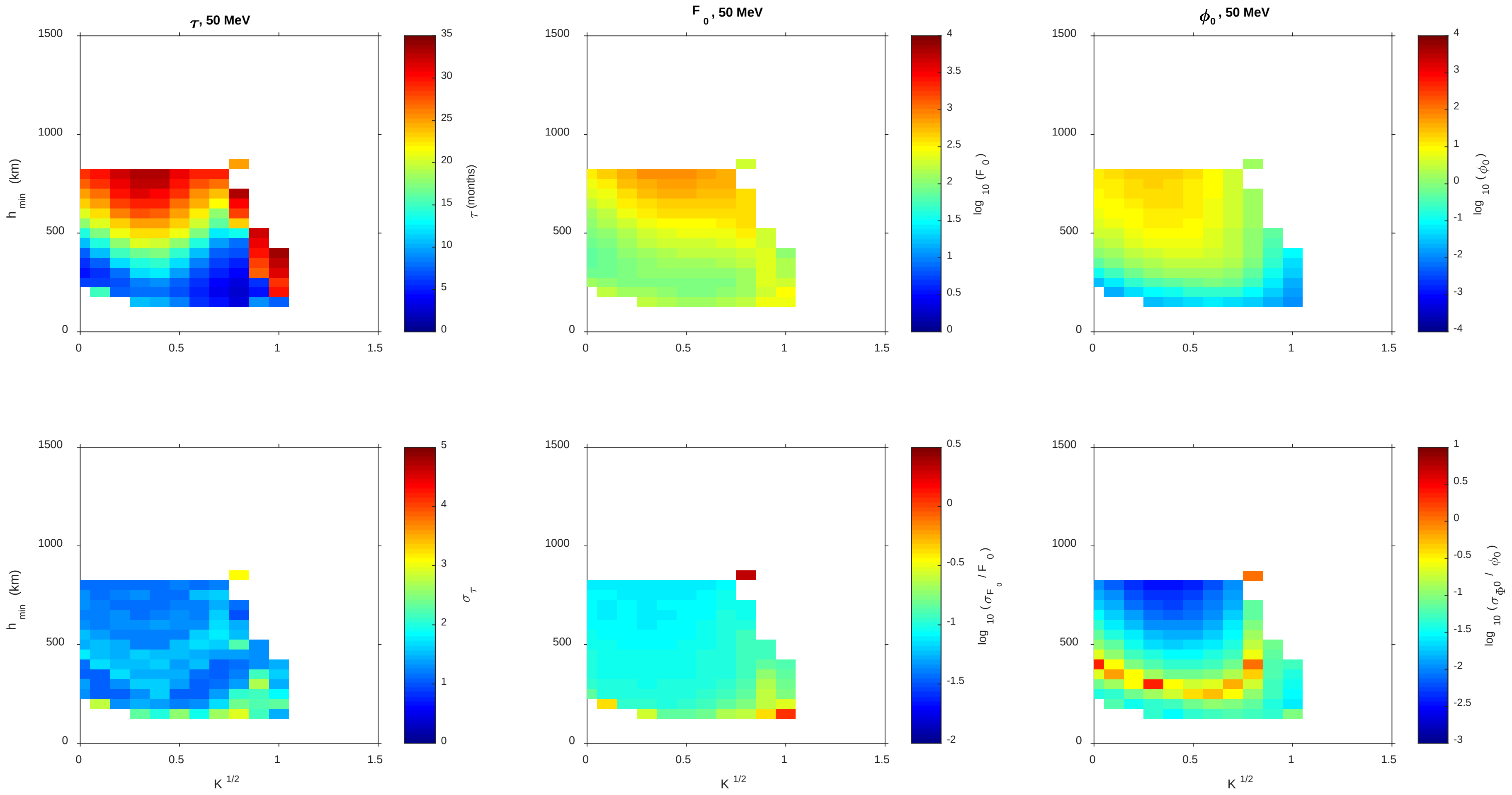
Fitting Parameters: SIZM



Top row is a parameter map in K/h_{min} space

Bottom row is an estimate of uncertainty

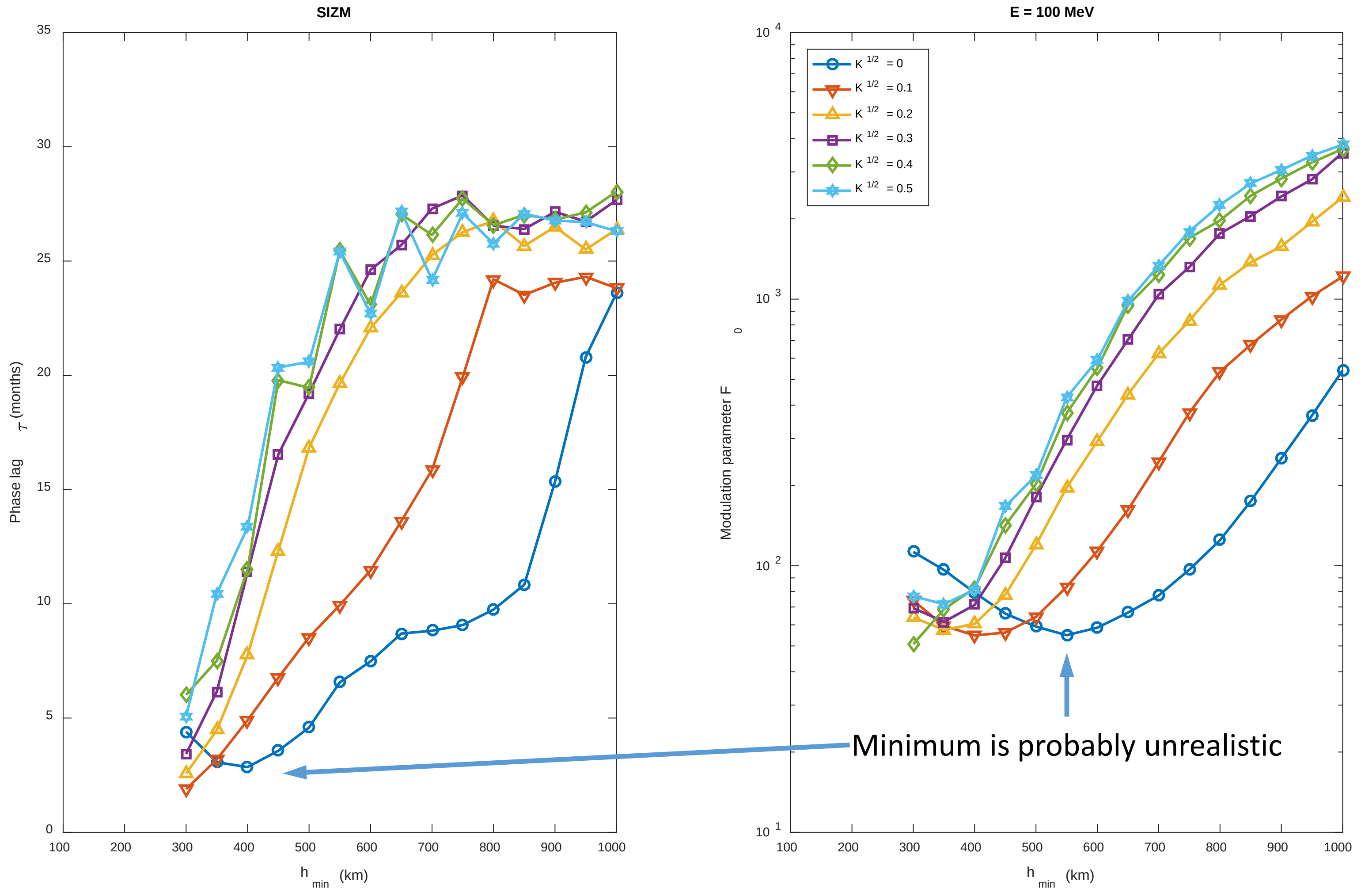
Fitting Parameters: POES



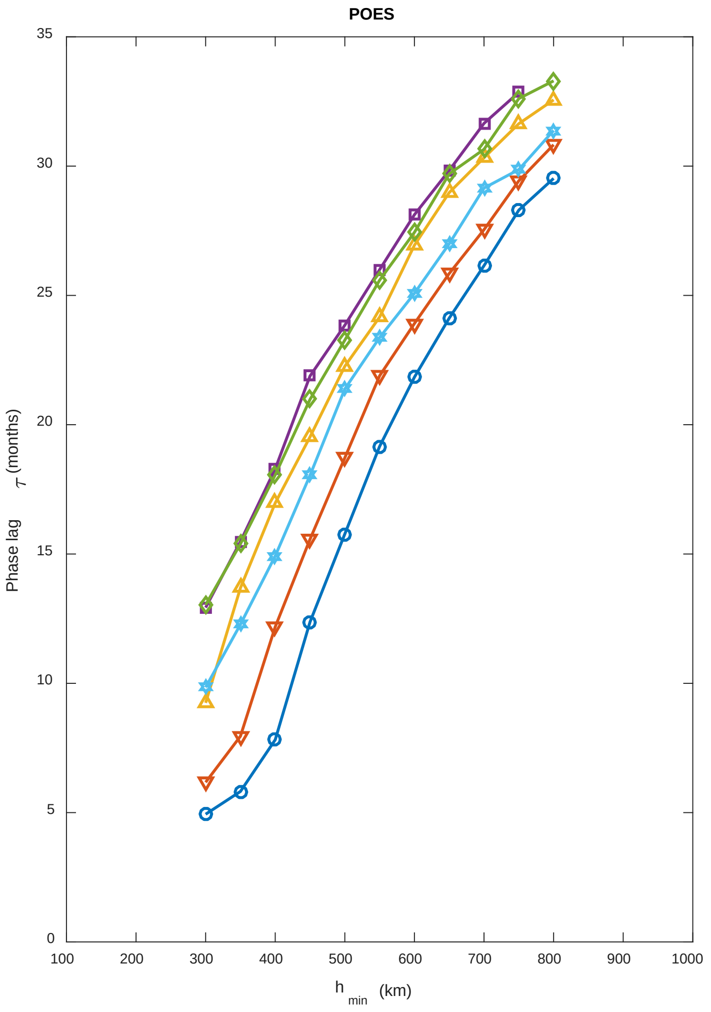
Top row is a parameter map in K/h_{min} space

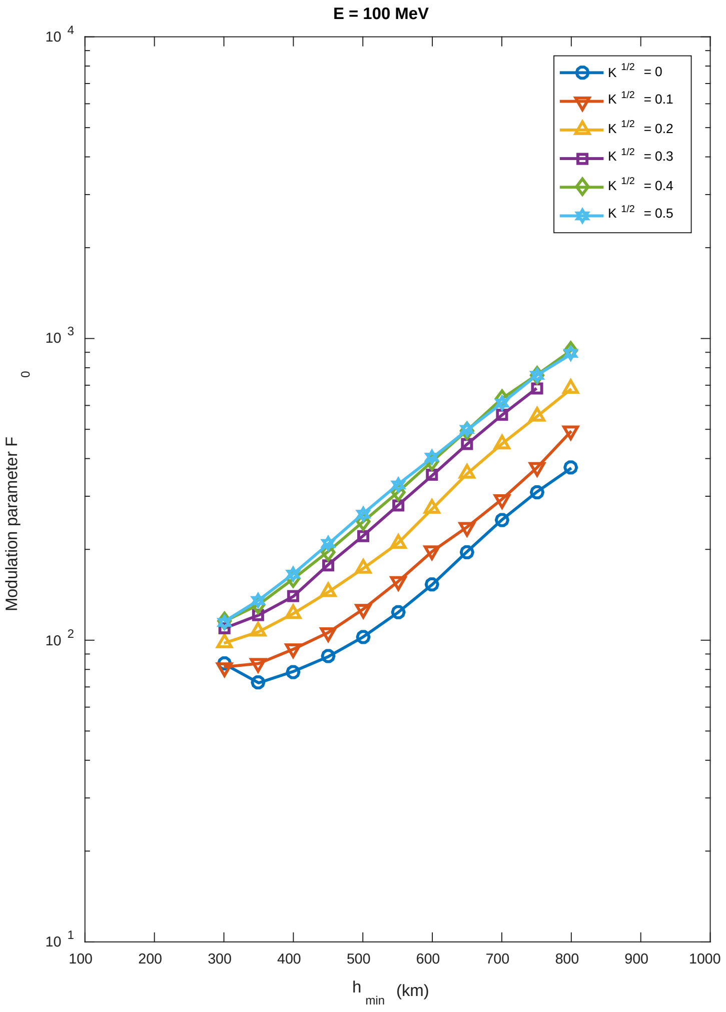
Bottom row is an estimate of uncertainty

τ, F_0 vs. h_{min}: SIZM

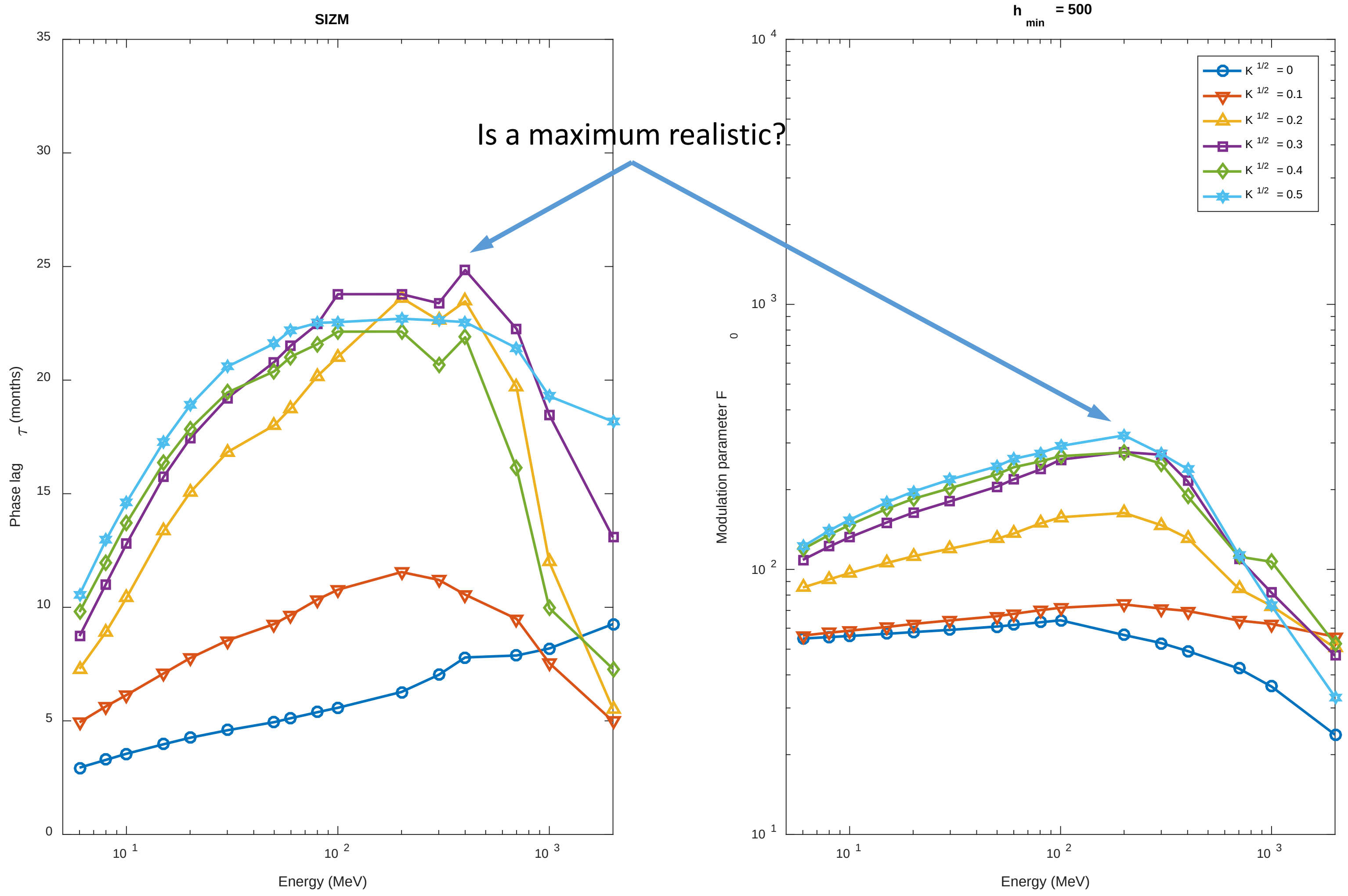


τ, F_0 vs. h_{min}: POES

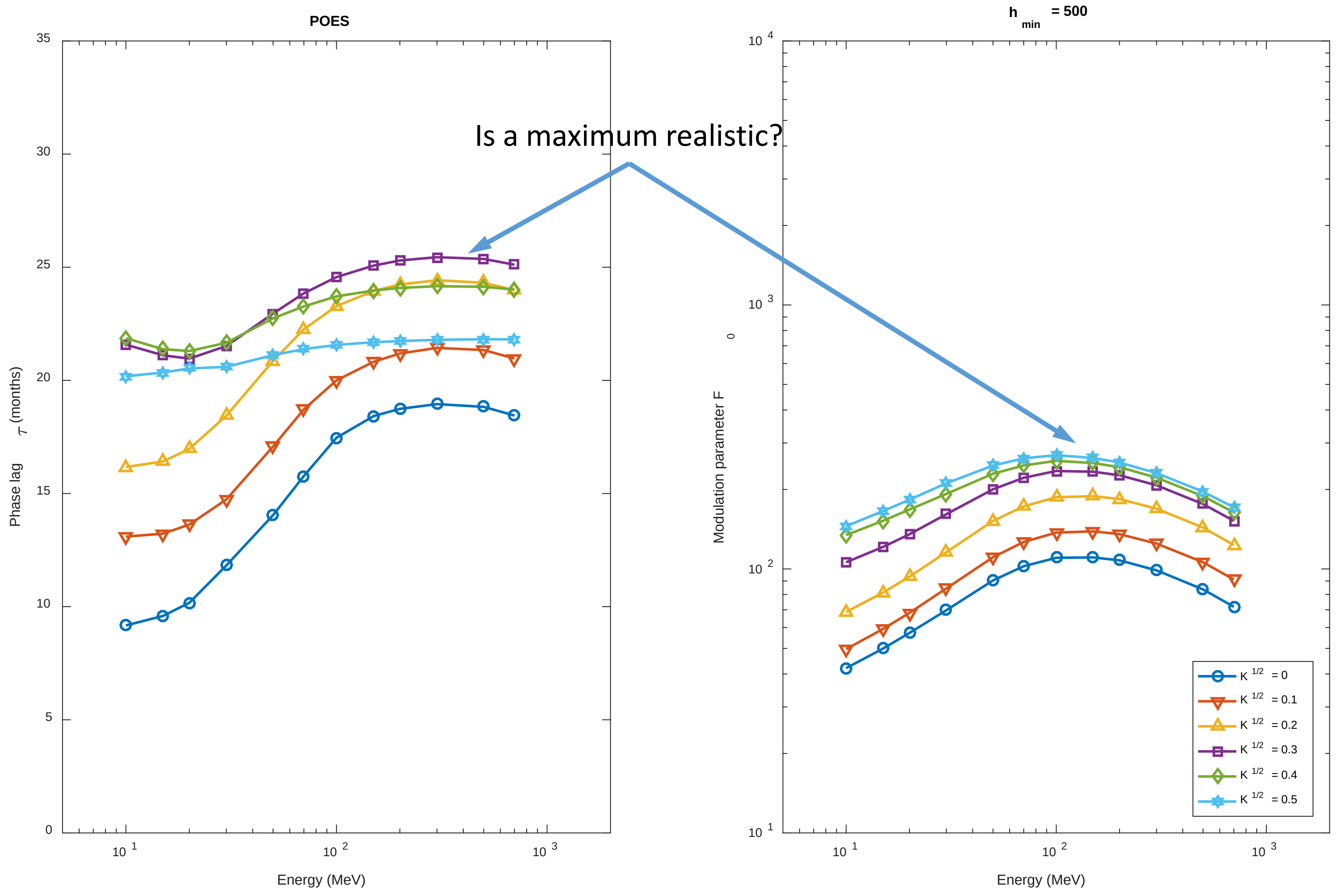




τ, F_0 vs. E: SIZM



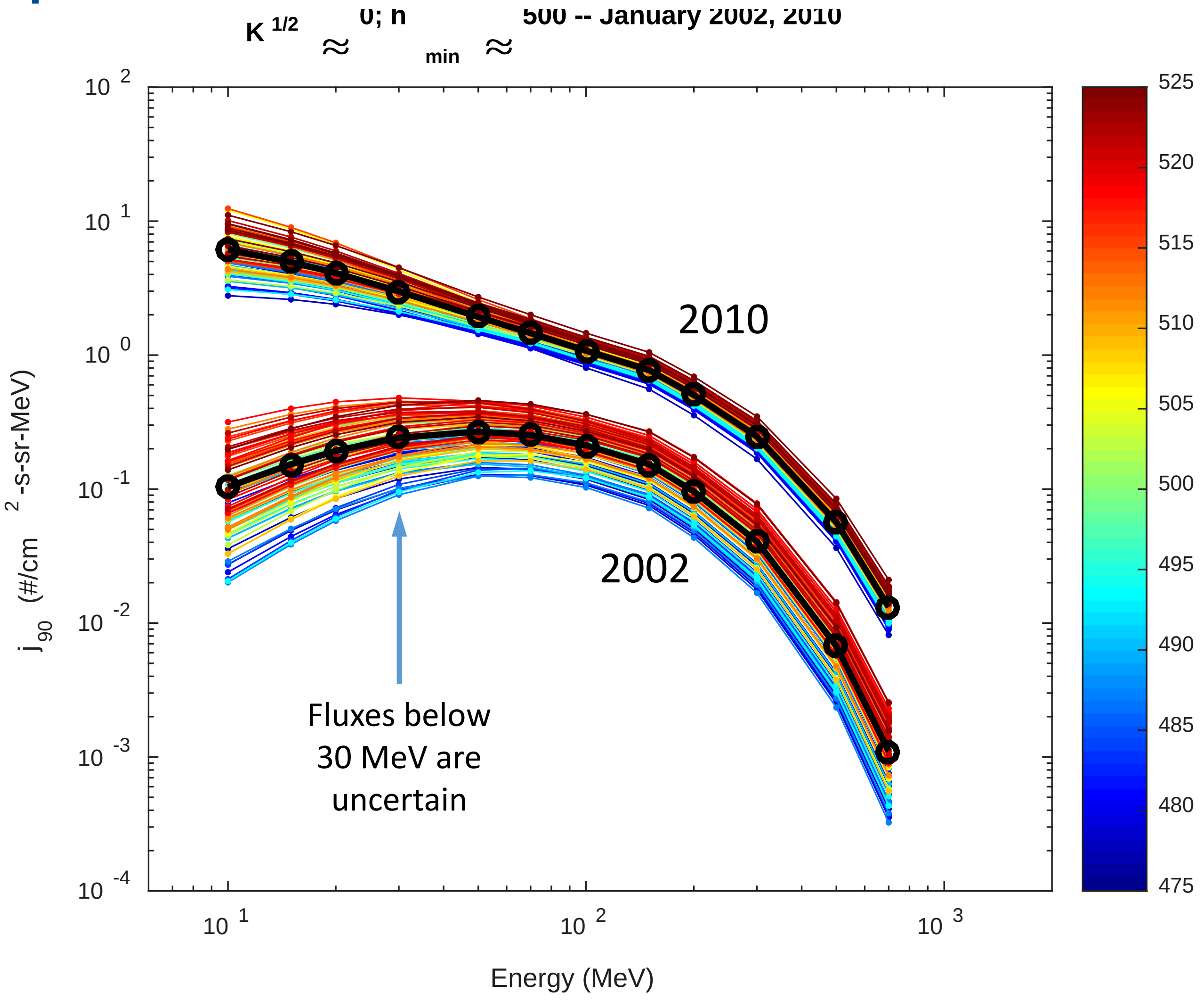
τ, F_0 vs. E: POES



Observations – POES vs. SIZM

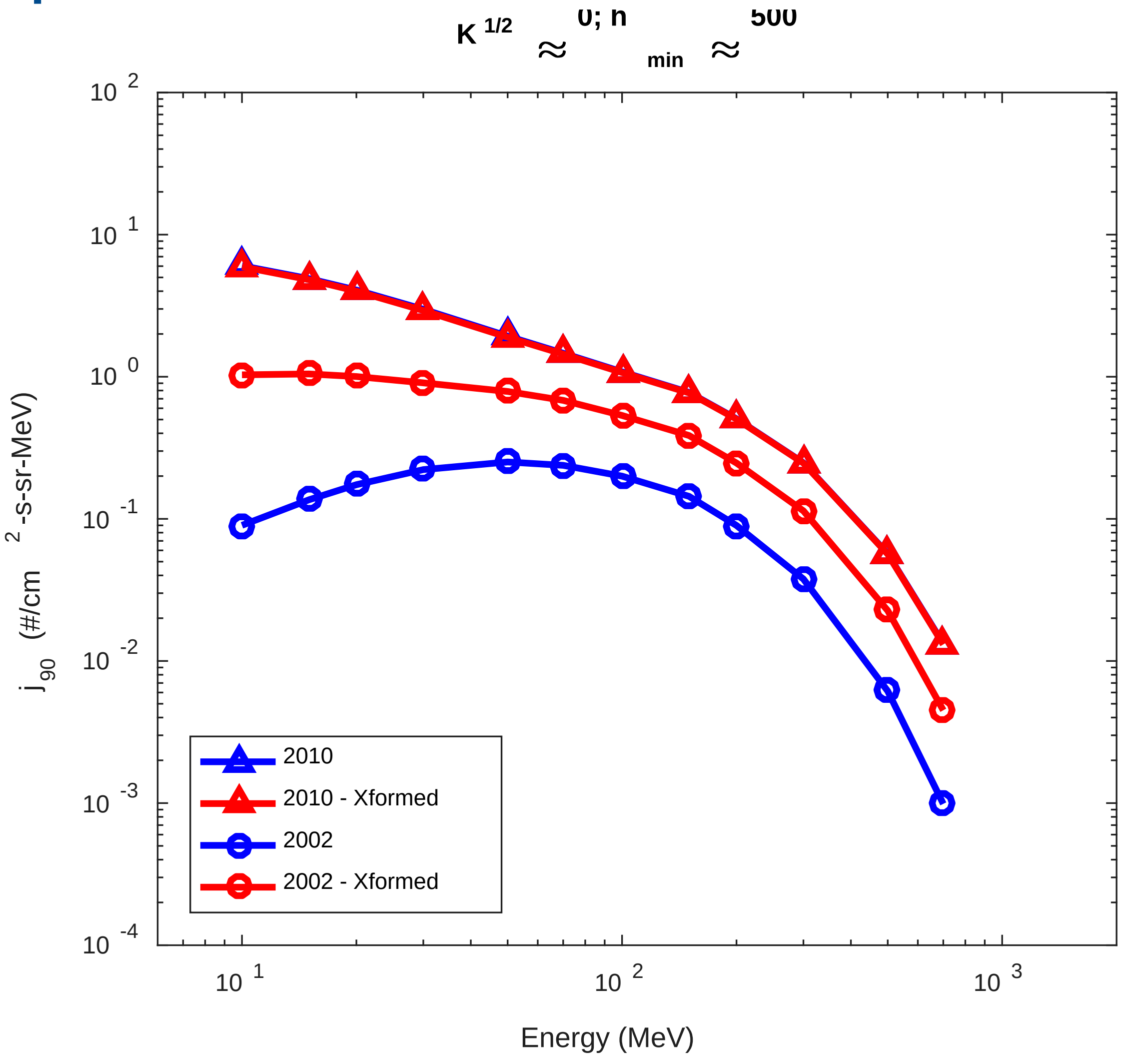
- Remember the man with two watches!
- SIZM generally has shorter phase lags than POES
- Modulation parameter is same order of magnitude, same trend for POES vs. SIZM
- POES trends are more self-consistent than SIZM
  - Possibly due to fewer solar cycles
  - Smoothing SIZM in E, K, h_{min} may help
- As solar cycle modulation becomes small (high altitude or high energy), fits become ambiguous
  - Phase lag increases w/energy (as expected), but levels off or decreases above 200 – 300 MeV
  - There is a maximum in modulation parameter at 100 – 500 MeV (POES & SIZM)

Example: POES inverted fluxes



- POES (NOAA-15) data in one bin, taken in January 2002 and January 2010
- Color scale indicates actual value of h_{min} – there is a significant variation in flux due to the finite size of bins

Example: Results



- Using POES fitting parameters, mean fluxes for 2002 and 2010 were transformed to $F_{10.7} = 70$
- Procedure accounts for much, but not all, of the difference between solar min and max

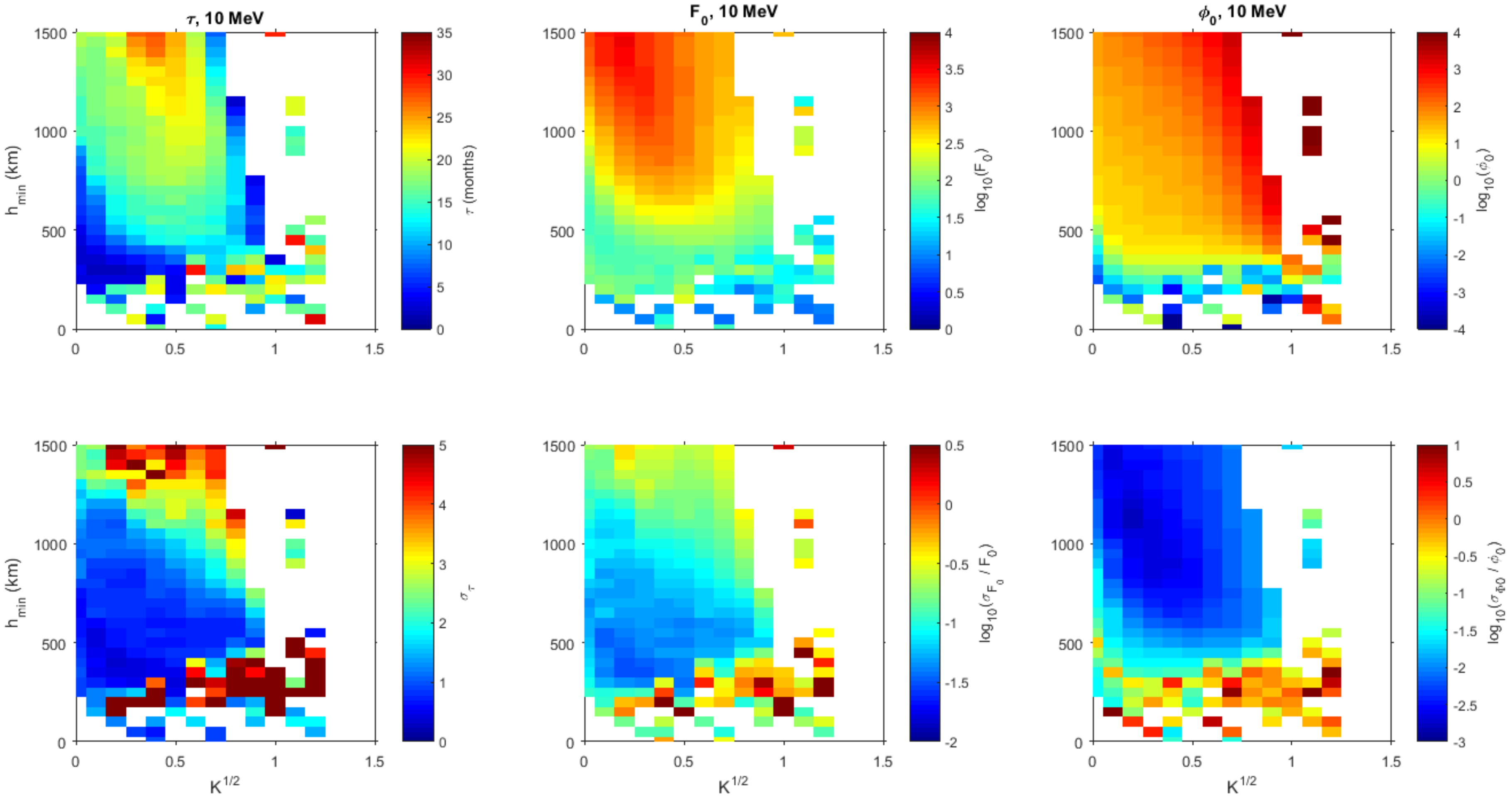
Next Steps

- Choose whether to use SIZM or POES (or somehow use both) or SAMPEX
- Extend parameters in E, K, h_{min}
  - Involves some major extrapolations plus physics-based insight
- Do more comparisons with other data sets (if possible)
- Will have to consider changes to model code
- Eventually will have to apply corrections to all low-altitude proton data sets and re-build flux maps

Backup Charts

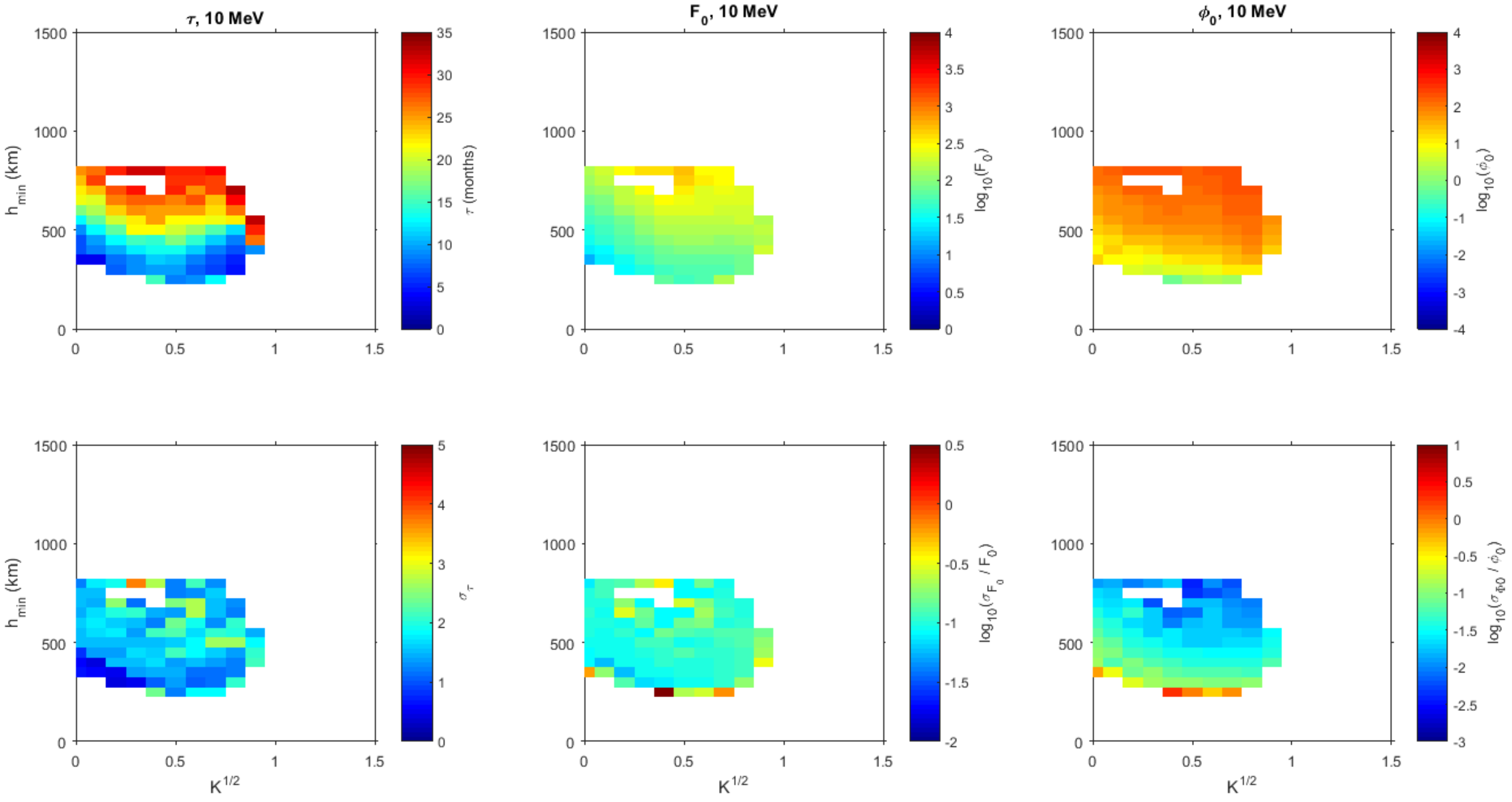
Fitting Parameters at Different Energies

SIZM, 10 MeV



τ, 10 MeV
F0, 10 MeV
φ0, 10 MeV
hmin (km)
τ (months)
log10(F0)
log10(φ0)
στ
log10(σF0 / F0)
log10(σΦ0 / φ0)
K1/2

POES, 10 MeV



τ, 10 MeV
F_0, 10 MeV
ϕ_0, 10 MeV
h_{min} (km)
τ (months)
$\log_{10}(F_0)$
$\log_{10}(\dot{\phi}_0)$
σ_τ
$\log_{10}(\sigma_{F_0} / F_0)$
$\log_{10}(\sigma_{\Phi 0} / \dot{\phi}_0)$
$K^{1/2}$

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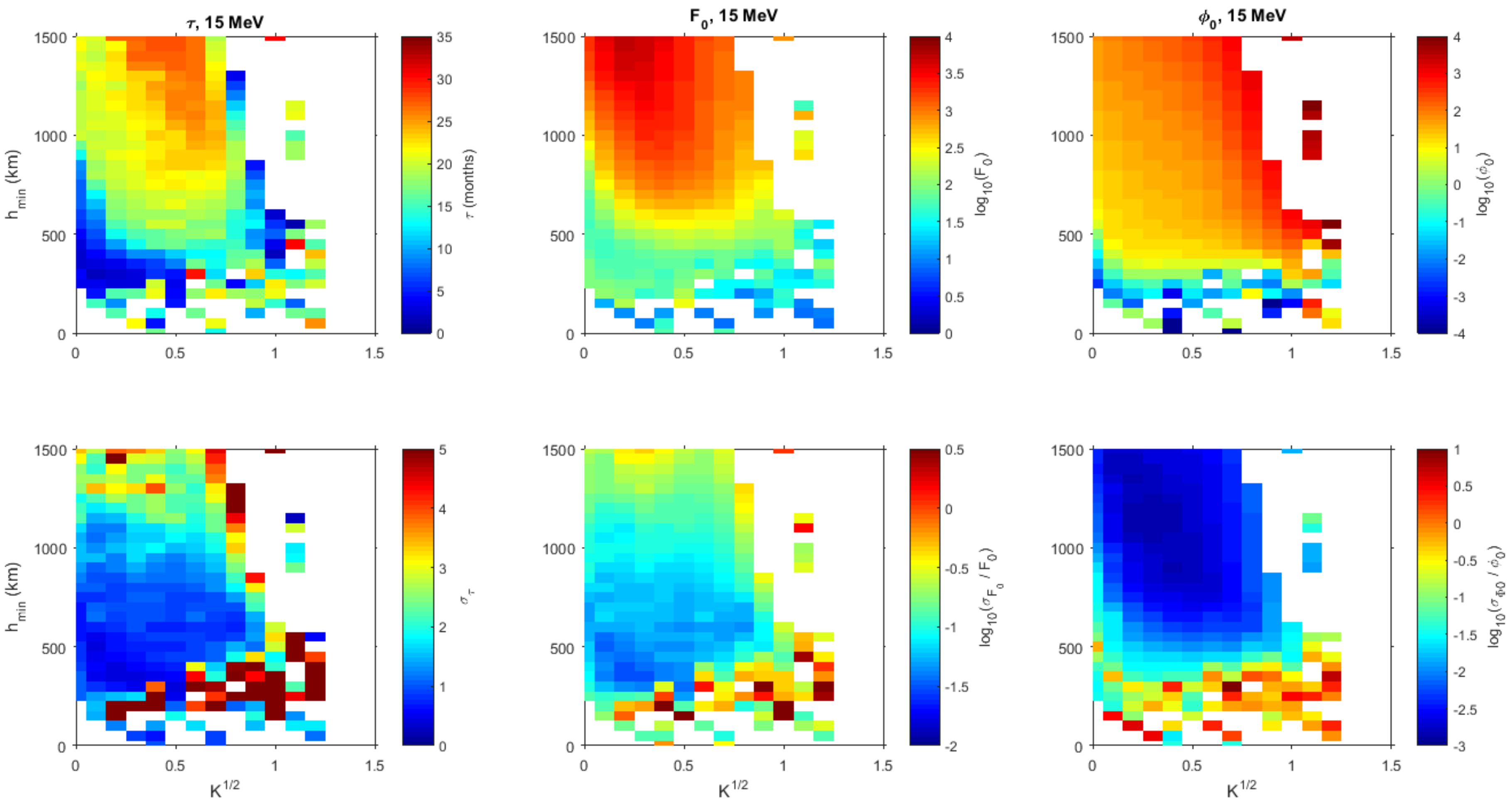
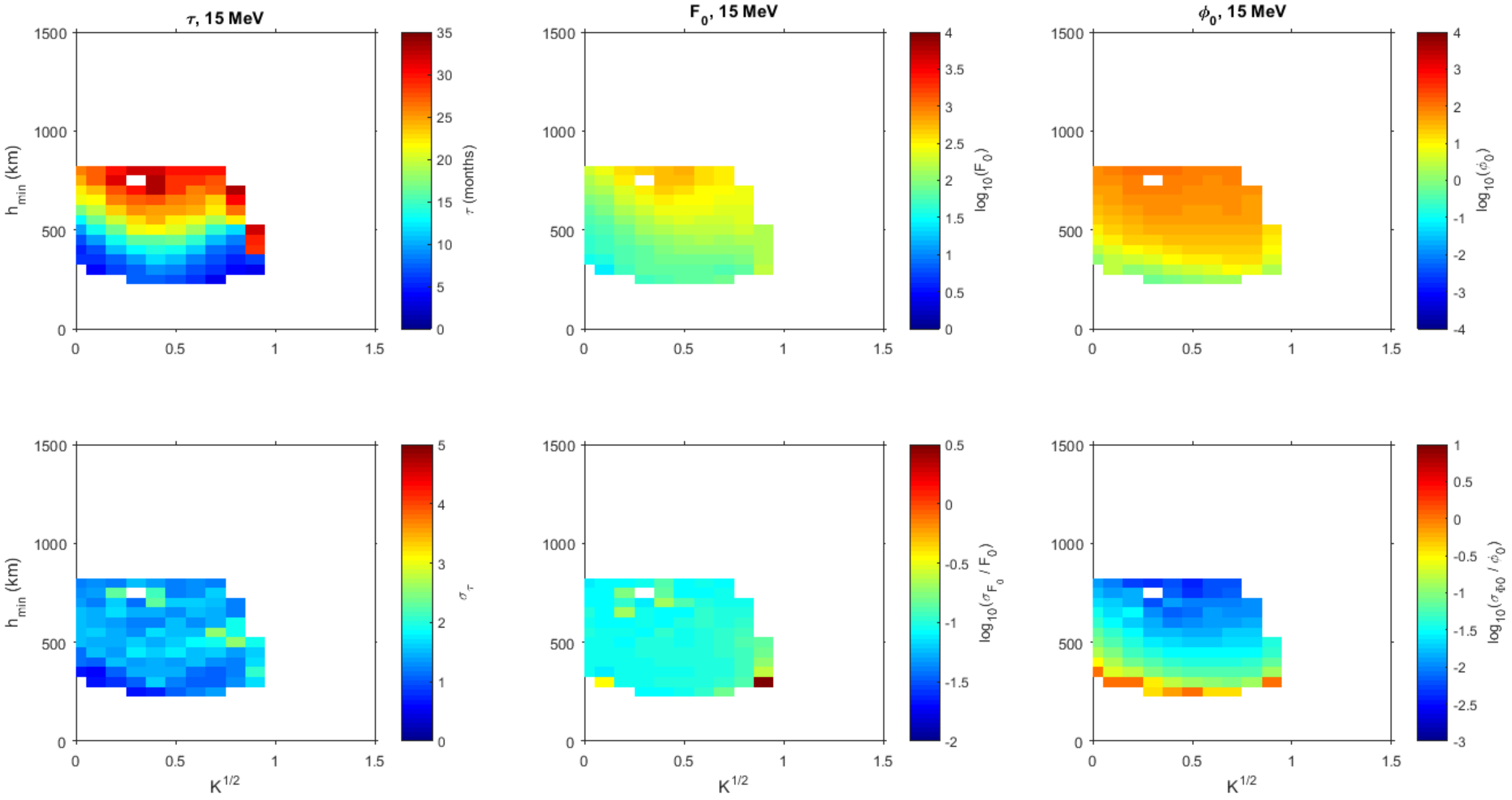
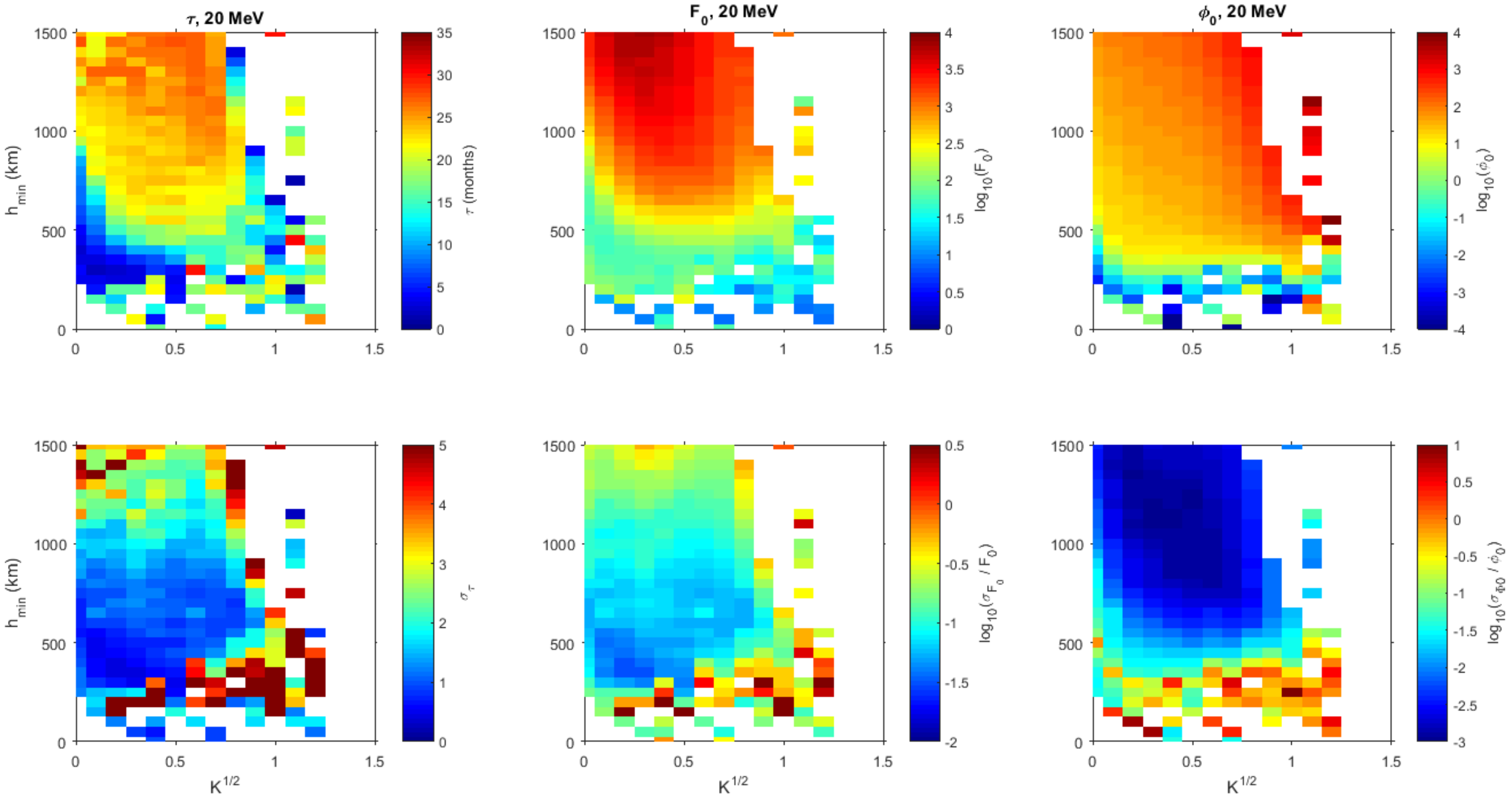
SIZM, 15 MeV



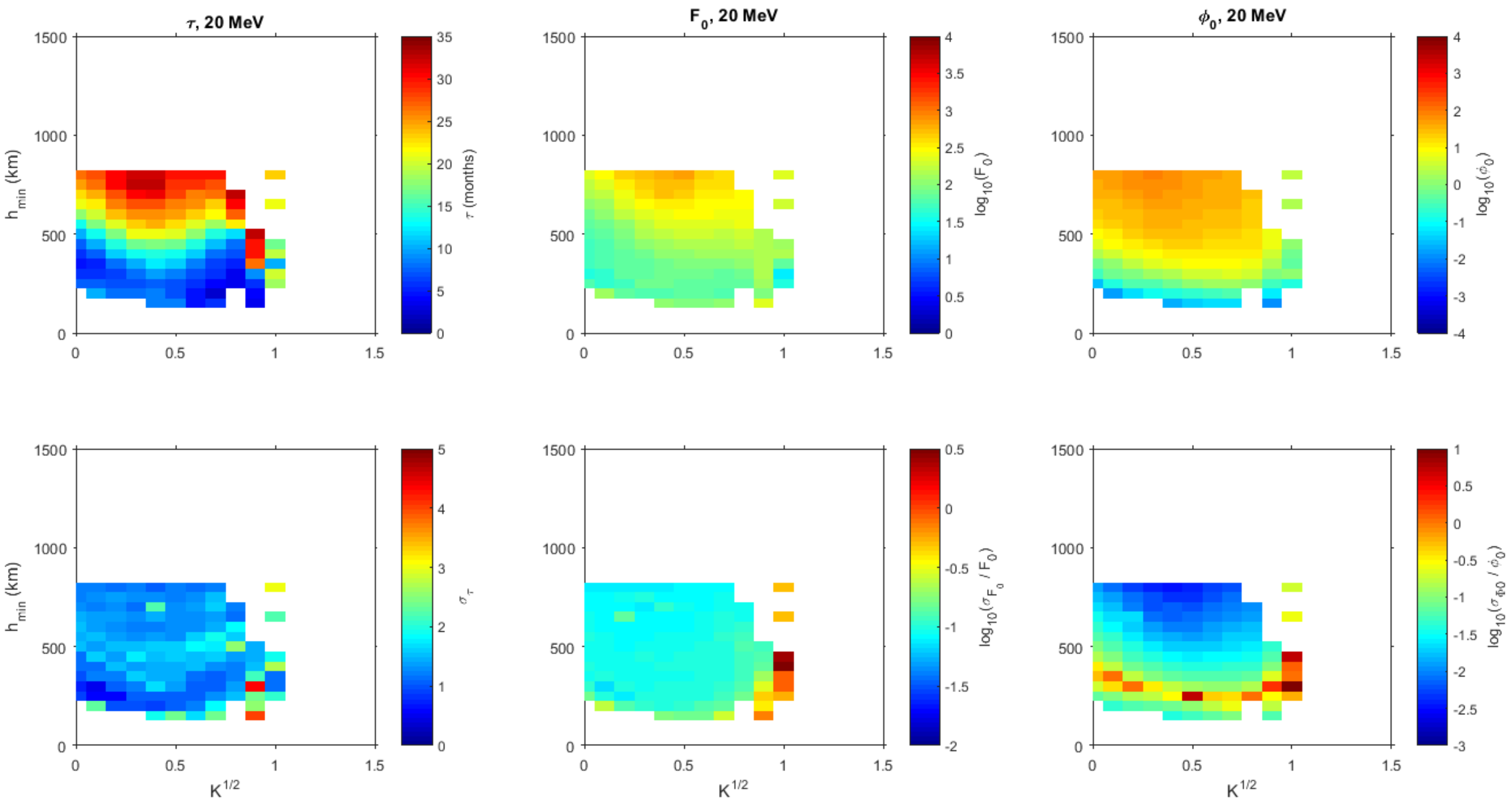
POES, 15 MeV


τ, 15 MeV
F0, 15 MeV
φ0, 15 MeV
h_min (km)
τ (months)
log10(F0)
log10(φ0)
στ
log10(σF0 / F0)
log10(σΦ0 / φ0)
K^1/2
1500
1000
500
0
0.5
1
1.5

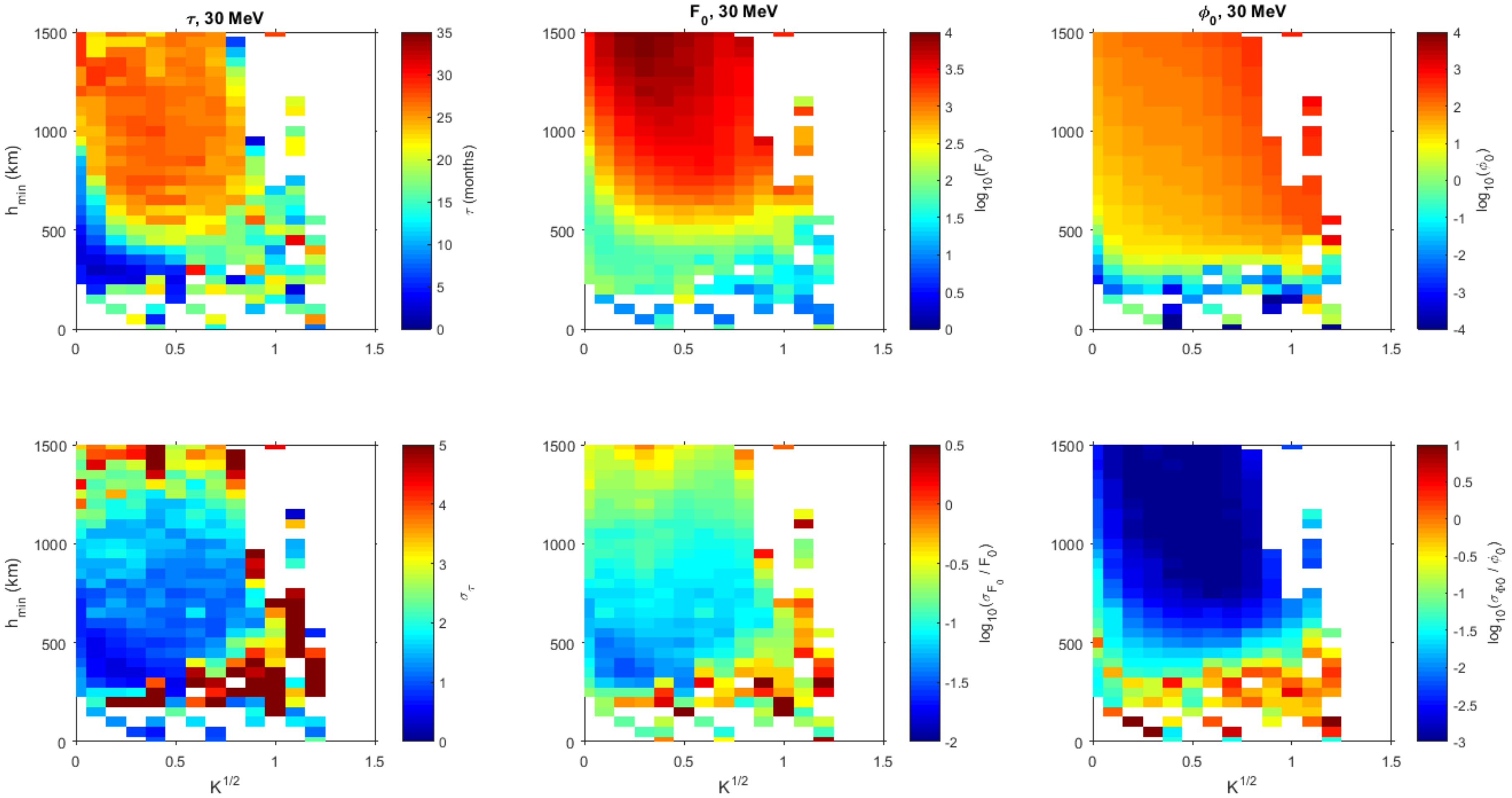
SIZM, 20 MeV


τ, 20 MeV
F0, 20 MeV
φ0, 20 MeV
hmin (km)
K1/2
τ (months)
log10(F0)
log10(φ0)
στ
log10(σF0 / F0)
log10(σΦ0 / φ0)

POES, 20 MeV

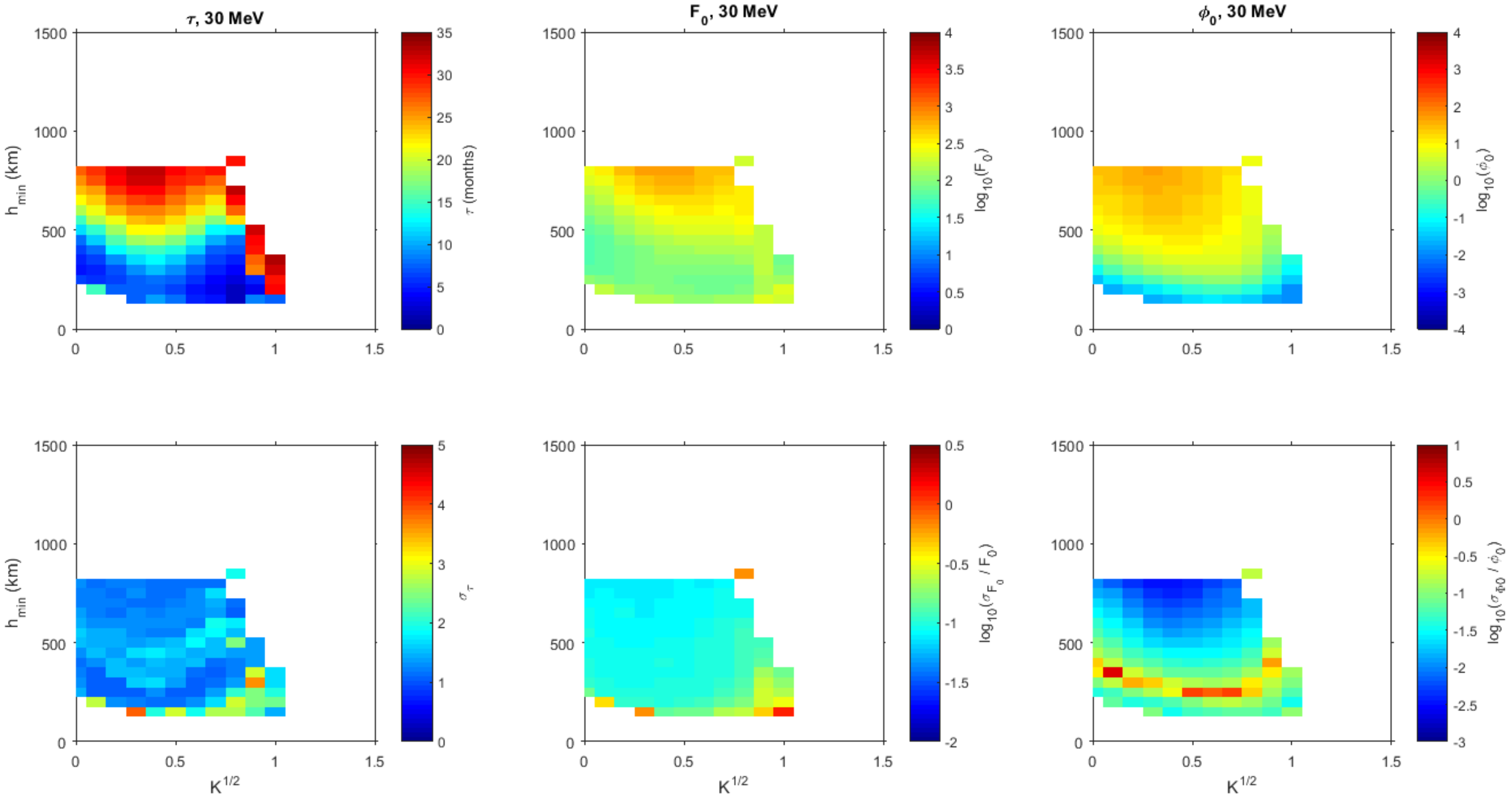

τ, 20 MeV
F0, 20 MeV
φ0, 20 MeV
h_min (km)
τ (months)
log10(F0)
log10(φ0)
σ_τ
log10(σ_F0 / F0)
log10(σ_Φ0 / φ0)
K^1/2

SIZM, 30 MeV



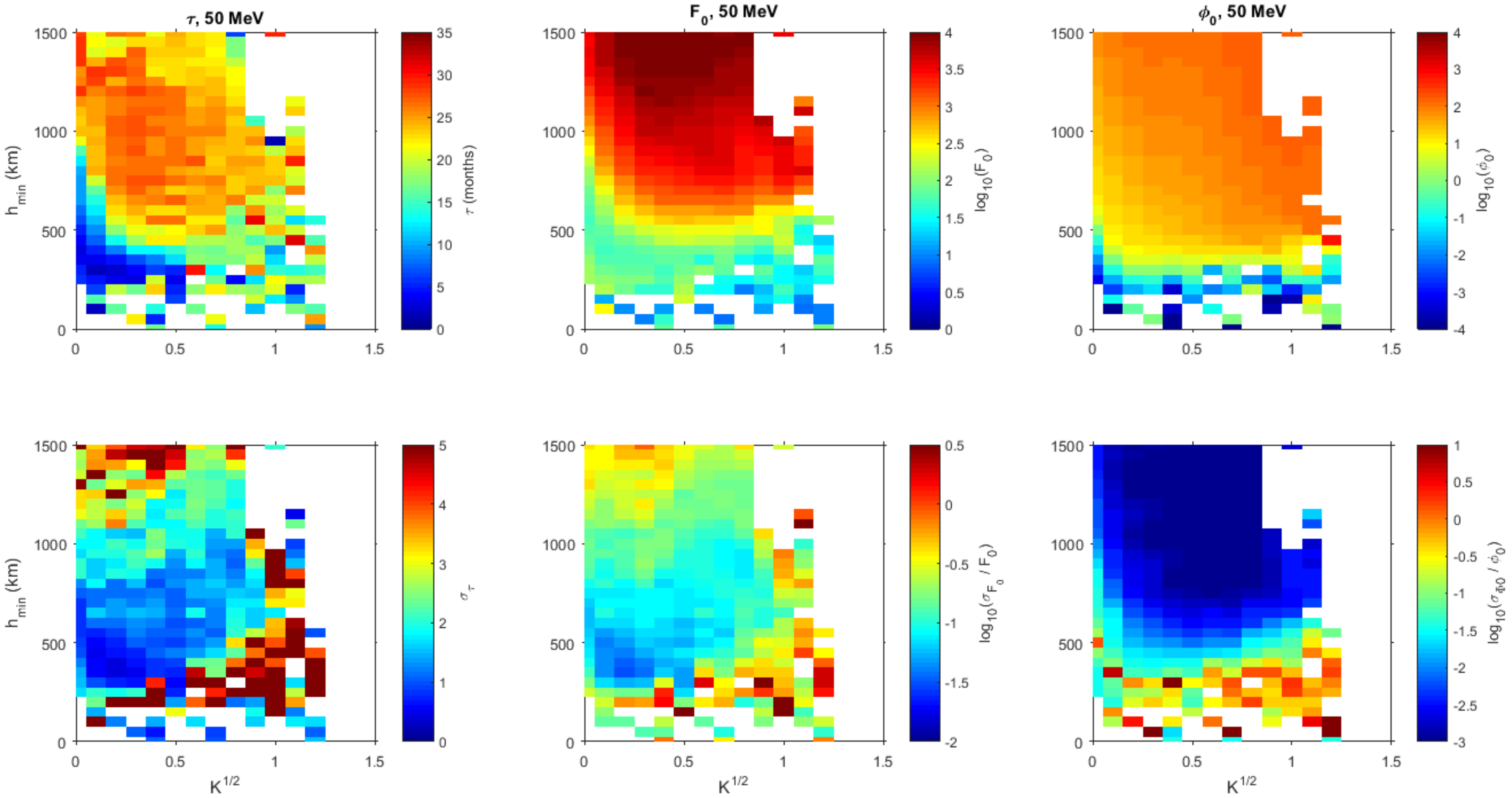
τ, 30 MeV
F_0, 30 MeV
ϕ_0, 30 MeV
h_{min} (km)
τ (months)
$\log_{10}(F_0)$
$\log_{10}(\phi_0)$
σ_τ
$\log_{10}(\sigma_{F_0} / F_0)$
$\log_{10}(\sigma_{\Phi 0} / \phi_0)$
$K^{1/2}$

POES, 30 MeV

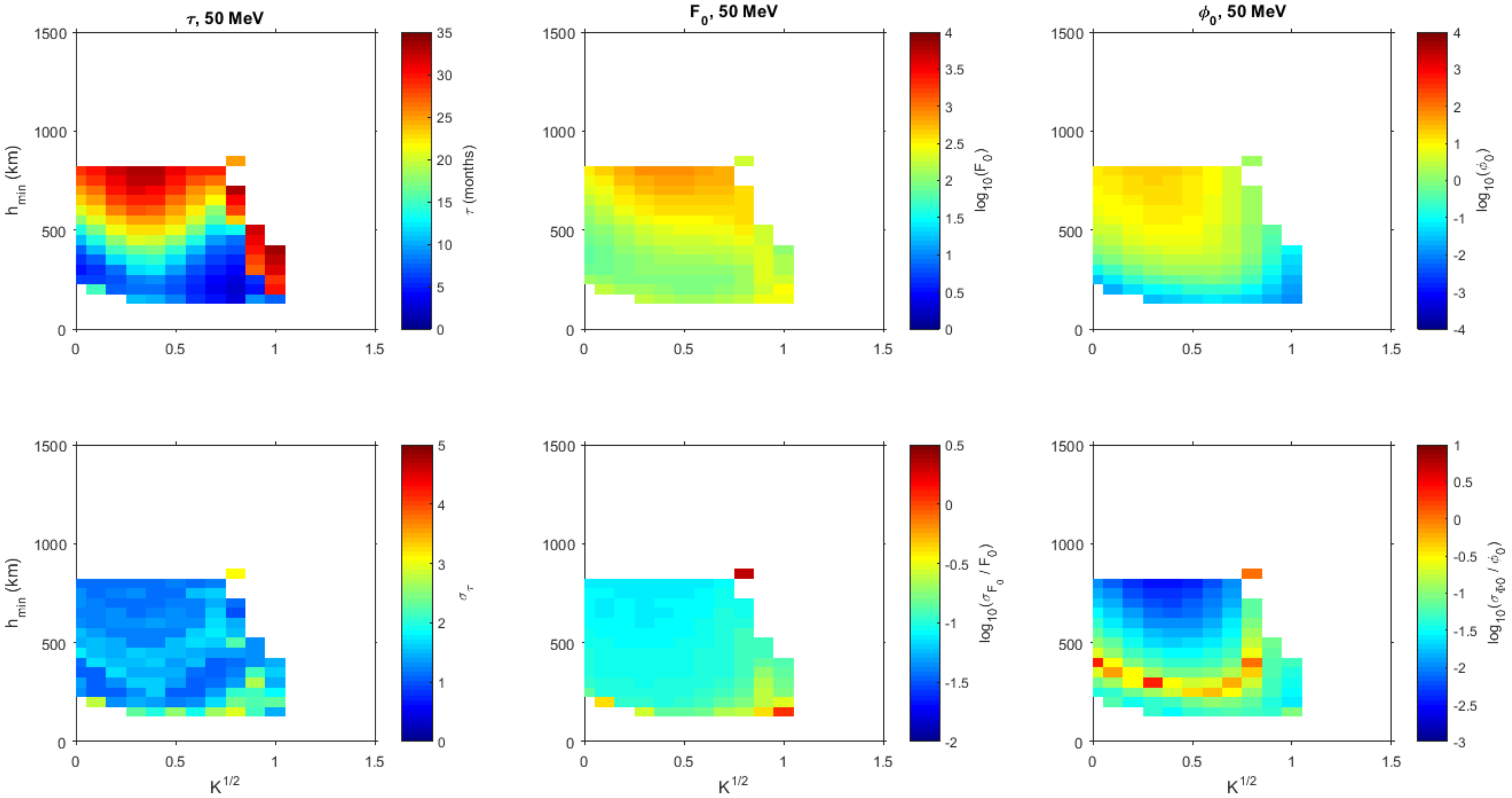


τ, 30 MeV
F0, 30 MeV
φ0, 30 MeV
hmin (km)
τ (months)
log10(F0)
log10(φ0)
στ
log10(σF0 / F0)
log10(σΦ0 / φ0)
K1/2

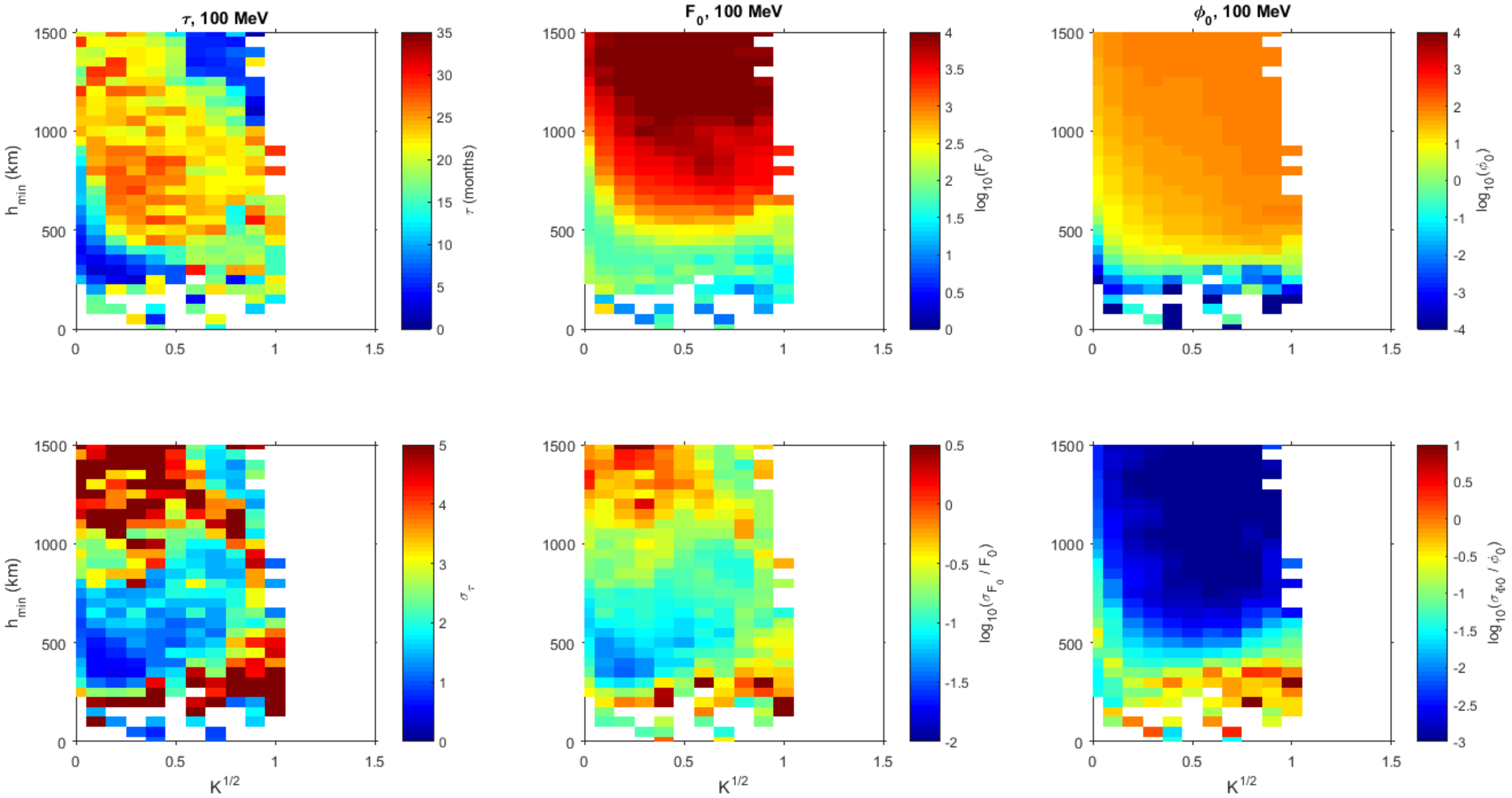
SIZM, 50 MeV


τ, 50 MeV
F0, 50 MeV
φ0, 50 MeV
hmin (km)
K1/2
τ (months)
log10(F0)
log10(φ0)
στ
log10(σF0 / F0)
log10(σΦ0 / φ0)

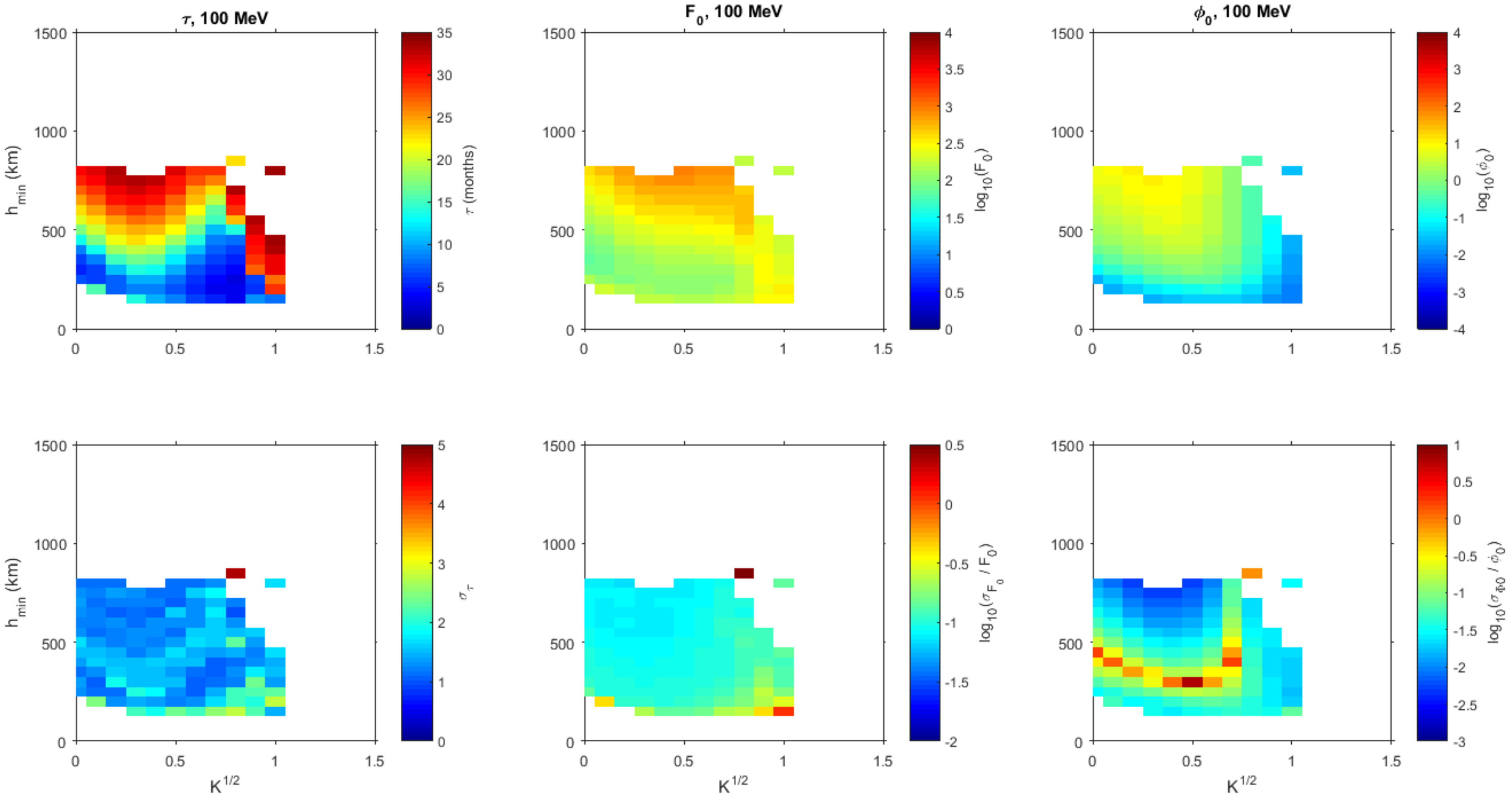
POES, 50 MeV


τ, 50 MeV
F0, 50 MeV
φ0, 50 MeV
hmin (km)
τ (months)
log10(F0)
log10(φ0)
στ
log10(σF0 / F0)
log10(σΦ0 / φ0)
K1/2
1500
1000
500
0
0.5
1
1.5

SIZM, 100 MeV

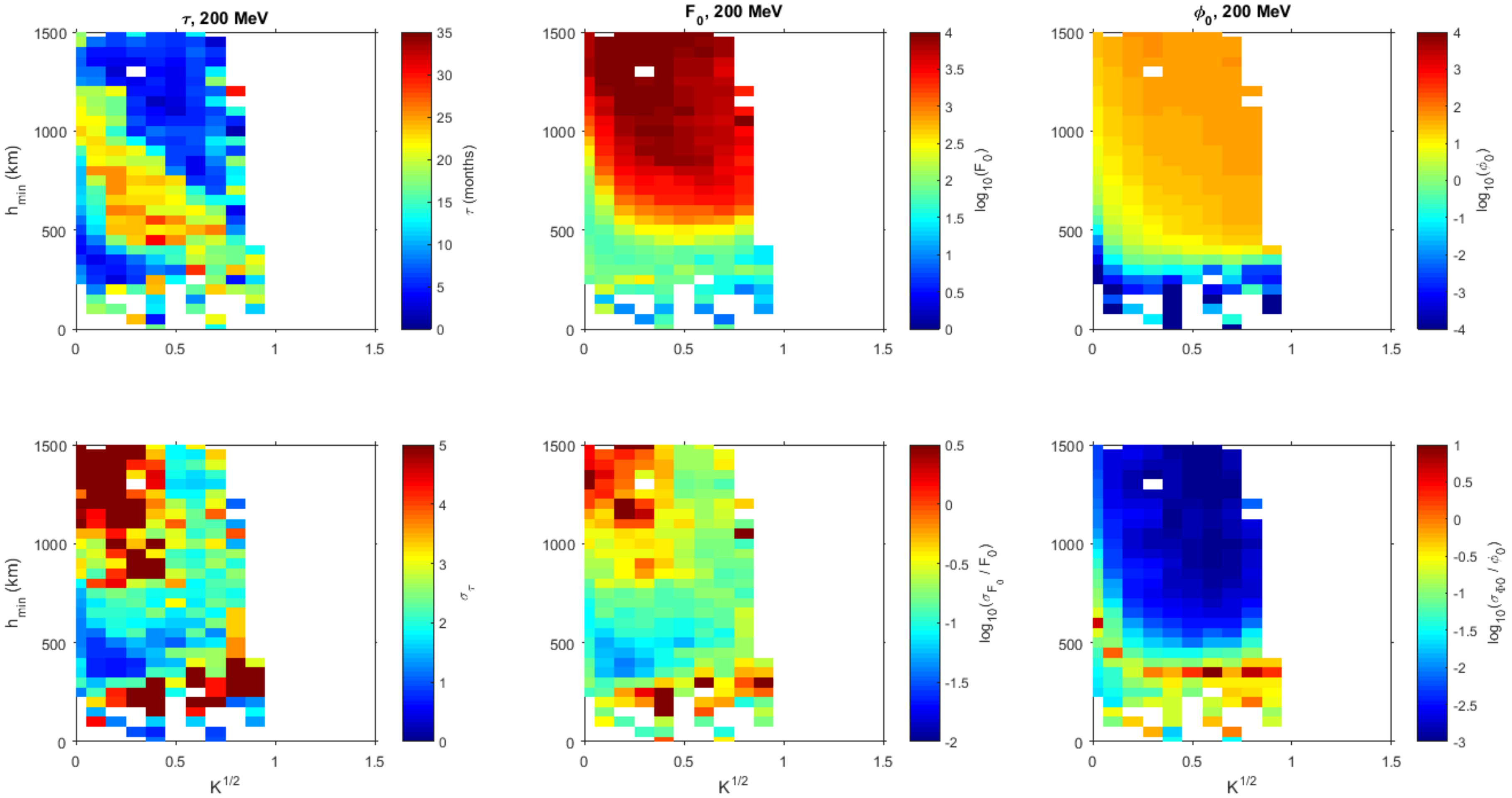

τ, 100 MeV
F_0, 100 MeV
ϕ_0, 100 MeV
h_{min} (km)
τ (months)
$\log_{10}(F_0)$
$\log_{10}(\phi_0)$
σ_τ
$\log_{10}(\sigma_{F_0} / F_0)$
$\log_{10}(\sigma_{\Phi 0} / \phi_0)$
$K^{1/2}$

POES, 100 MeV



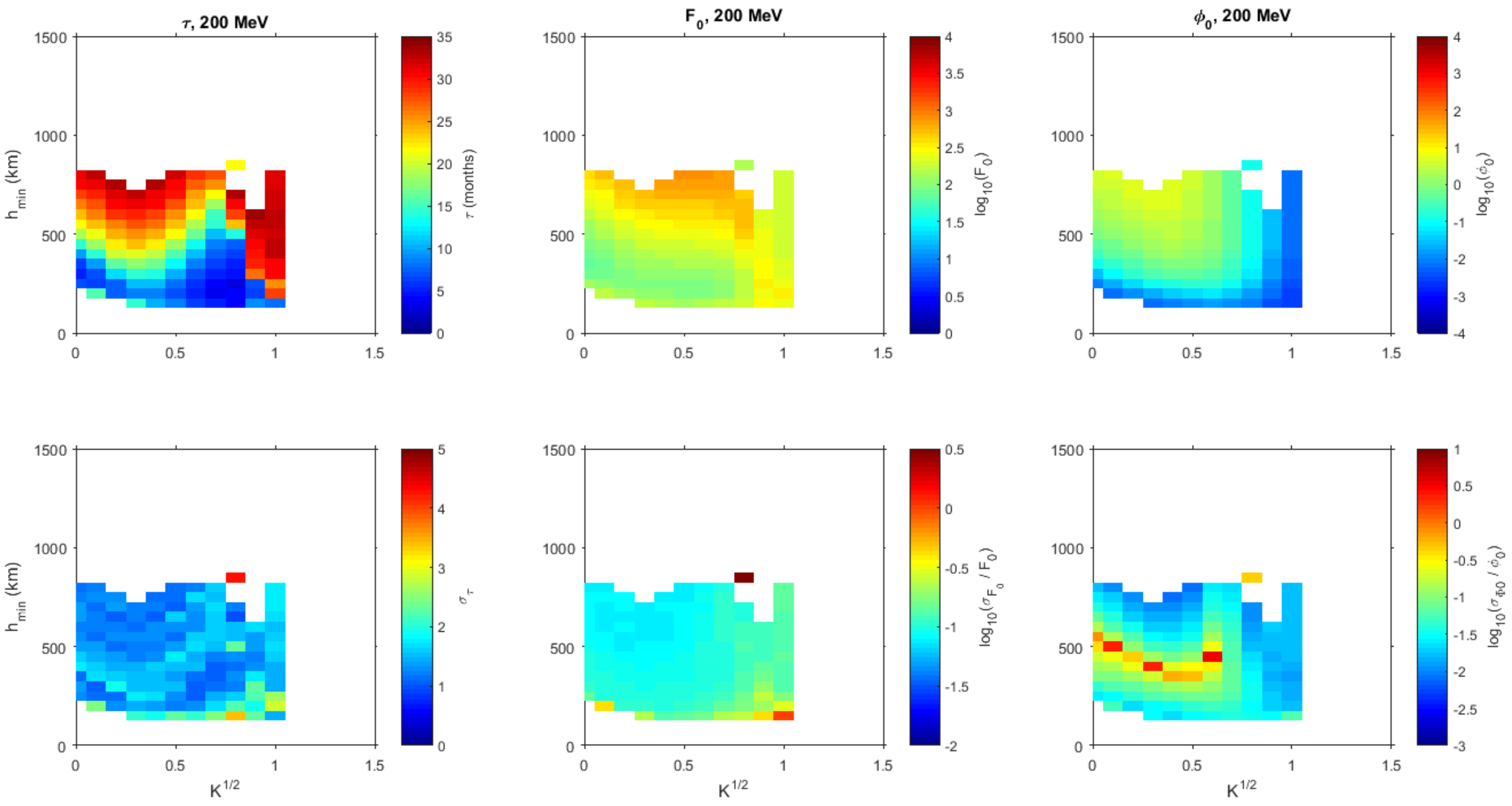
τ, 100 MeV
F0, 100 MeV
φ0, 100 MeV
h_min (km)
K^1/2
τ (months)
log10(F0)
log10(φ0)
στ
log10(σF0 / F0)
log10(σφ0 / φ0)

SIZM, 200 MeV

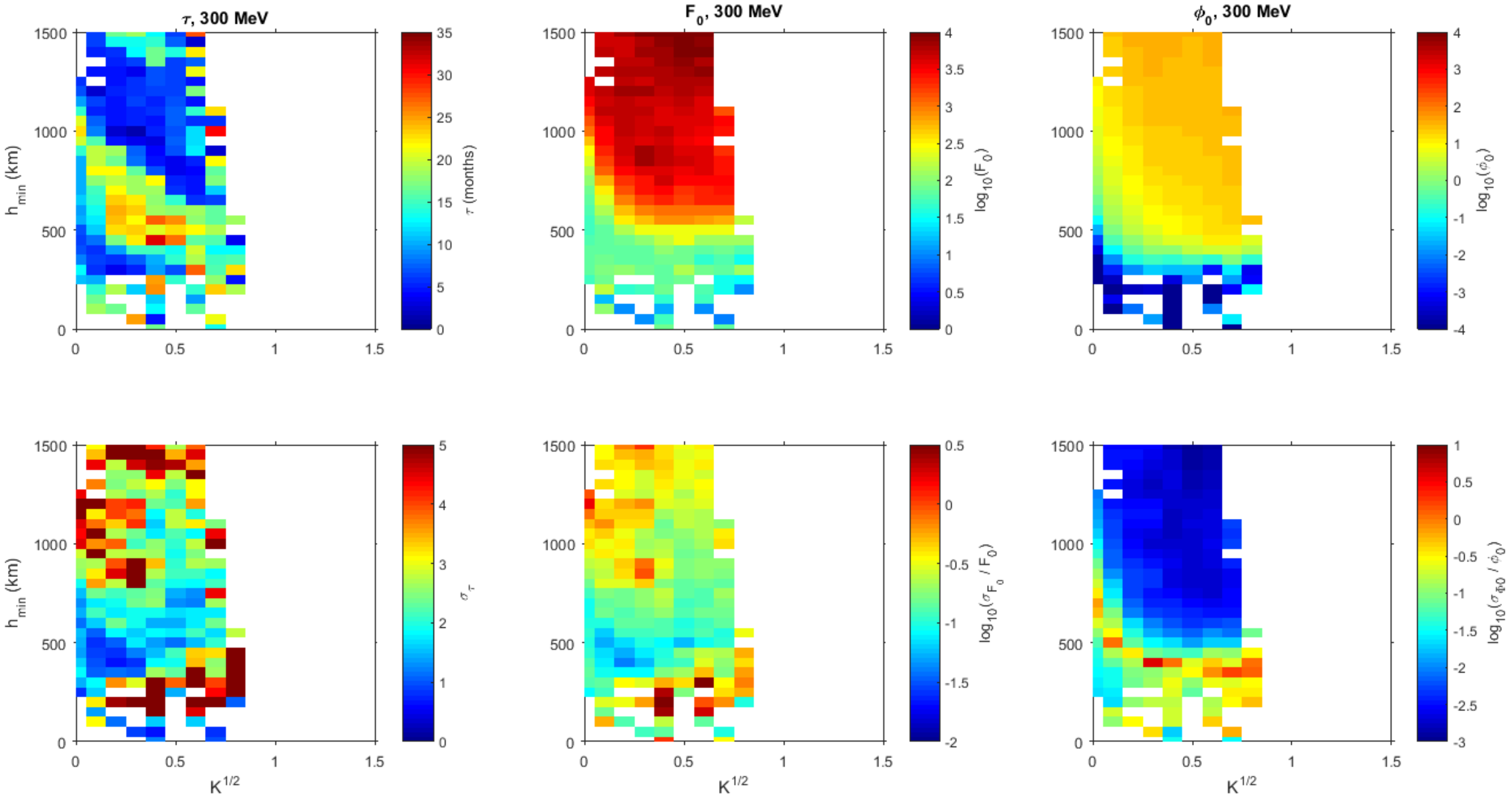

τ, 200 MeV
F0, 200 MeV
φ0, 200 MeV
hmin (km)
K1/2
τ (months)
log10(F0)
log10(φ0)
στ
log10(σF0 / F0)
log10(σΦ0 / φ0)
0
0.5
1
1.5
500
1000
1500

AFRL

POES, 200 MeV

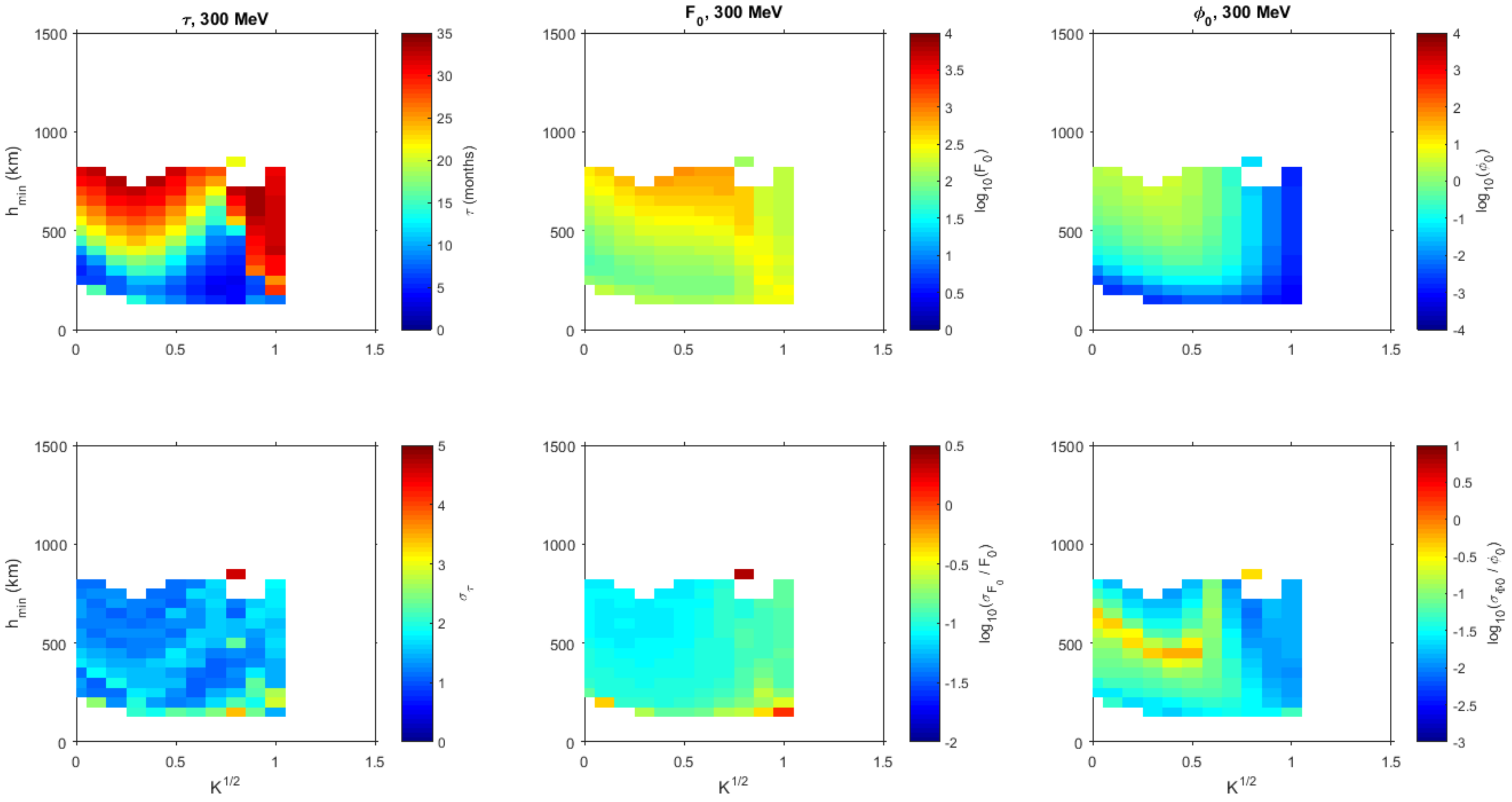


SIZM, 300 MeV

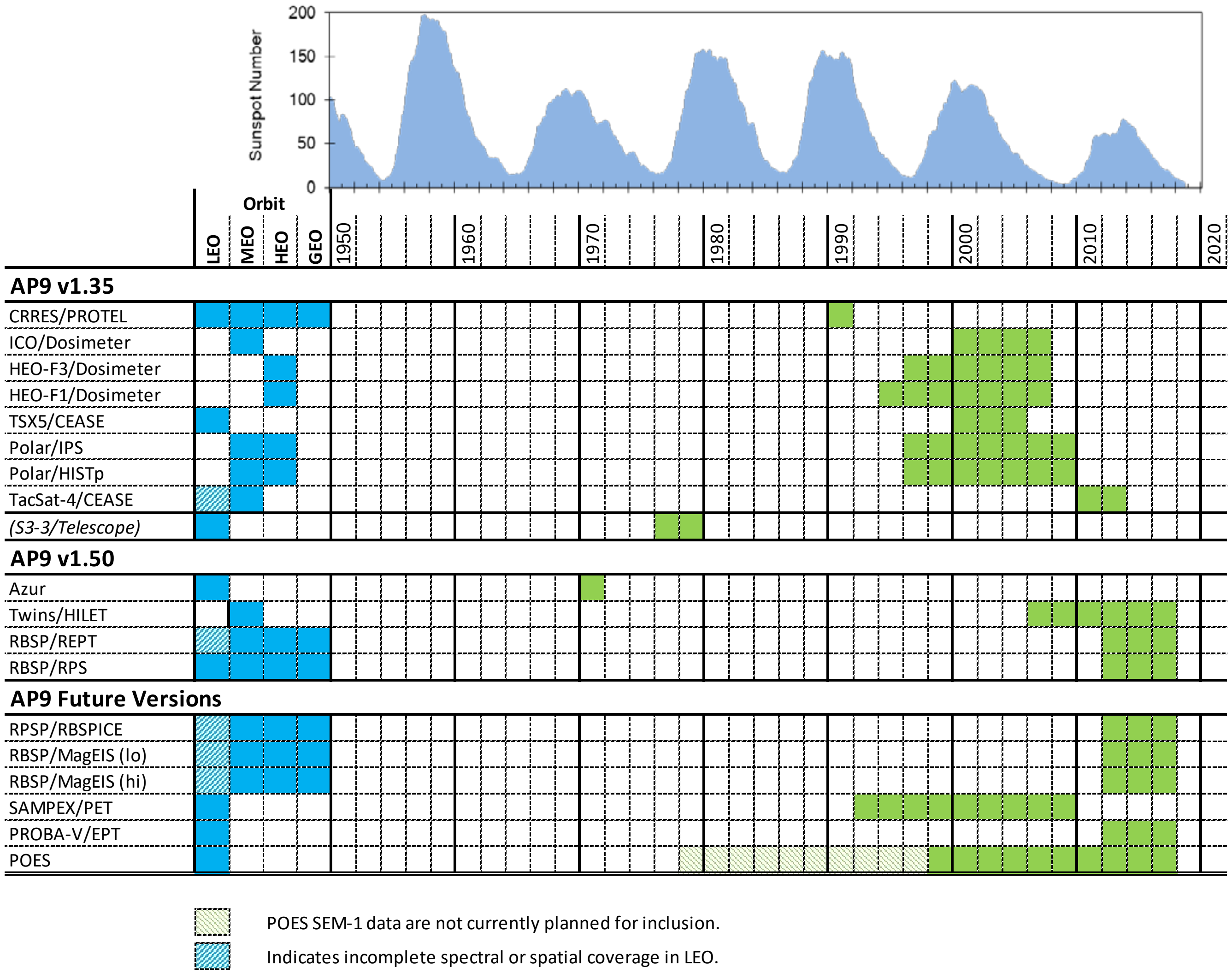

τ, 300 MeV
F0, 300 MeV
φ0, 300 MeV
hmin (km)
K1/2
τ (months)
log10(F0)
log10(φ0)
στ
log10(σF0 / F0)
log10(σΦ0 / φ0)
1500
1000
500
0
0.5
1
1.5

AFRL

POES, 300 MeV



Proton Datasets – Temporal



Proton Datasets – Energy