Three Myths about Empirical Models

- Myth #1: There is no physics in empirical models.
- Myth #2: Empirical models cannot describe short-term variations.
- Myth #3: Empirical models are not very useful scientifically.
- Bonus Myth: Scatter in the data will obscure systematic behavior

U.S. NAVAL RESEARCH LABORATORY

John Emmert
Space Science Division
Naval Research Laboratory
john.emmert@nrl.navy.mil

(With helpful input from the workshop speakers)

Acknowledgement: This work was supported by the Chief of Naval Research

Myth #1: There is no physics in empirical models.

Reality:
Almost all major empirical models have foundational physical constraints. Examples:

- International Geomagnetic Reference Field (IGRF): No magnetic source terms above Earth's surface.

$$\nabla^2 V = 0$$

$$\mathbf{B} = -\vec{\nabla} V$$

- MSIS, DTM atmosphere models: Hydrostatic and diffusive equilibrium (connects temperature and density data).

$$dP = -\rho g dz$$

Converse myth: There is no data in first-principles models
Reality: All first-principles models employ empirical parameterizations (including major empirical models) to represent:

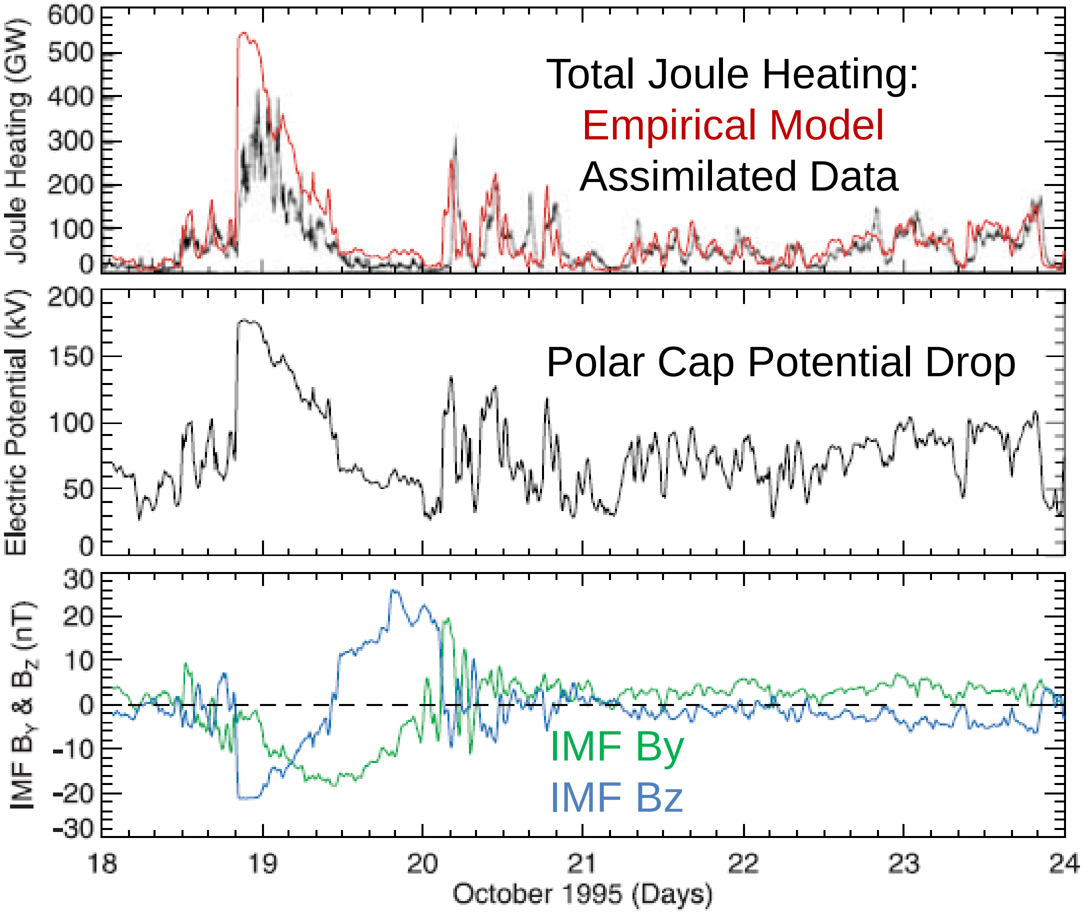
- Subgrid-scale processes
- Background conditions
- Boundary conditions
- Initial conditions

Myth #2: Empirical models cannot describe short-term variations (aka “It’s just climatology”).

Reality:

- Empirical models can describe the average observed <u>response</u> to geophysical drivers, not just the time-averaged state of the system.
- If the drivers are changing rapidly, the empirical model will change rapidly, too.

Example: Weimer high-latitude electric potential model



Weimer, JGR 2005

Myth #3: Empirical models are not very useful scientifically.

Reality:

Empirical models are indispensable scientific tools whose diverse uses include:

- Prediction of geophysical conditions at specific times
- A distilled view of the historical observational record
- A benchmark for assessing new measurement techniques and first-principles models
- Boundary and initial conditions for first-principles models
- Interpolation among sparse observations
- Attribution of observed variations
- First guess (Bayesian prior) for measurement retrievals
- Background conditions for other models (e.g., wave propagation)

Empirical model papers are among the most widely cited in the literature…

Most-cited papers in JGR Space Physics

= Empirical Model Papers

1. **EXTENSION OF THE MSIS THERMOSPHERE MODEL INTO THE MIDDLE AND LOWER ATMOSPHERE**
By: HEDIN, AE
JOURNAL OF GEOPHYSICAL RESEARCH-SPACE PHYSICS Volume: 96 Issue: A2 Pages: 1159-1172
Published: FEB 1 1991
NRL LINX | Full Text from Publisher | View Abstract
Times Cited: 1,588 *(from Web of Science Core Collection)*
Usage Count

2. **MSIS-86 THERMOSPHERIC MODEL**
By: HEDIN, AE
JOURNAL OF GEOPHYSICAL RESEARCH-SPACE PHYSICS Volume: 92 Issue: A5 Pages: 4649-4662
Published: MAY 1 1987
NRL LINX | Full Text from Publisher
Times Cited: 1,370 *(from Web of Science Core Collection)*
Usage Count

3. **MAGNETIC LOOP BEHIND AN INTER-PLANETARY SHOCK - VOYAGER, HELIOS, AND IMP-8 OBSERVATIONS**
By: BURLAGA, L; SITTLER, E; MARIANI, F; et al.
JOURNAL OF GEOPHYSICAL RESEARCH-SPACE PHYSICS Volume: 86 Issue: NA8 Pages: 6673-6684
Published: 1981
NRL LINX | Full Text from Publisher
Times Cited: 894 *(from Web of Science Core Collection)*
Usage Count

4. **NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues**
By: Picone, JM; Hedin, AE; Drob, DP; et al.
JOURNAL OF GEOPHYSICAL RESEARCH-SPACE PHYSICS Volume: 107 Issue: A12 Article Number: 1468
Published: DEC 24 2002
NRL LINX | Full Text from Publisher | View Abstract
Times Cited: 824 *(from Web of Science Core Collection)*
Usage Count

5. **AMPLITUDE DISTRIBUTION OF FIELD-ALIGNED CURRENTS AT NORTHERN HIGH LATITUDES OBSERVED BY TRIAD**
By: IIJIMA, T; POTEMRA, TA
JOURNAL OF GEOPHYSICAL RESEARCH-SPACE PHYSICS Volume: 81 Issue: 13 Pages: 2165-2174
Published: 1976
NRL LINX | Full Text from Publisher
Times Cited: 780 *(from Web of Science Core Collection)*
Usage Count

6. **WHAT IS A GEOMAGNETIC STORM**
By: GONZALEZ, WD; JOSELYN, JA; KAMIDE, Y; et al.
JOURNAL OF GEOPHYSICAL RESEARCH-SPACE PHYSICS Volume: 99 Issue: A4 Pages: 5771-5792
Published: APR 1 1994
NRL LINX | Full Text from Publisher | View Abstract
Times Cited: 772 *(from Web of Science Core Collection)*
Usage Count

7. **EMPIRICAL HIGH-LATITUDE ELECTRIC-FIELD MODELS**
By: HEPPNER, JP; MAYNARD, NC
JOURNAL OF GEOPHYSICAL RESEARCH-SPACE PHYSICS Volume: 92 Issue: A5 Pages: 4467-4489
Published: MAY 1 1987
NRL LINX | Full Text from Publisher
Times Cited: 763 *(from Web of Science Core Collection)*
Usage Count

8. **EMPIRICAL RELATIONSHIP BETWEEN INTERPLANETARY CONDITIONS AND DST**
By: BURTON, RK; MCPHERRON, RL; RUSSELL, CT
JOURNAL OF GEOPHYSICAL RESEARCH-SPACE PHYSICS Volume: 80 Issue: 31 Pages: 4204-4214
Published: 1975
NRL LINX | Full Text from Publisher
Times Cited: 753 *(from Web of Science Core Collection)*
Usage Count

Bonus Myth: Scatter in the data will obscure systematic behavior

Reality:

- Empirical models successfully and fundamentally describe the average (climatological) observed behavior of the system, including short-term systematic responses.
- Stochastic or chaotic variations (i.e. weather) are largely averaged out in the processing.
- From a systems perspective, empirical models of climate can be viewed as follows:

$$Y_j = \mu_j \underbrace{\left(x_1, x_2, x_3, \ldots, x_n \right)}_{\text{Drivers}} + \varepsilon_j$$

Climate variable j
- State properties (e.g., temperature)
- Variational properties (e.g., tidal amplitude)

Climate of j
- Deterministic
- Represents mean response of system to drivers
- Expectation value

Drivers
- Functional form can be nonlinear
- Can include time history of drivers

"Weather" of j
- Stochastic
- May depend on history of Y_j.
- Includes deterministic effects omitted from μ.

When comparing data or first-principles models with empirical models, keep in mind:

- Disagreement between a small number of measurements and an empirical model does not invalidate the empirical model.
- Agreement over a short time period between first-principles and empirical models does not validate the first-principals model.
- Averaged point-for-point comparisons provide the most rigorous assessment of data-model biases and model-model biases.
- The uncertainty of the mean is the relevant statistic.

Geospace Empirical Model Tutorials

Time	Speaker	Title	Model Output
1330	John Emmert	Overview: 3 Myths about Empirical Models	
1335	Stefan Maus	International Geomagnetic Reference Field (IGRF)	Background magnetic field vector
1352	John Emmert	NRLMSIS Atmosphere Temperature and Composition Model	Atmospheric neutral temperature, density, and composition
1407	Jens Oberheide	Climatological Tidal Model of the Thermosphere (CTMT)	Diurnal and semidiurnal tidal amplitude and phase (temperature, wind, density)
1424	Doug Drob	Horizontal Wind Model (HWM)	Atmospheric horizontal neutral wind vector
1439	Dieter Bilitza	International Reference Ionosphere (IRI)	Electron and ion density, composition, and temperature; vertical electron column density
1456	Dan Weimer	High-latitude Electric field and Current Models	Electric potential, field-aligned currents, Poynting flux, geomagnetic field perturbations
1513	Paul O'Brien	AE-9/AP-9 Radiation Belt Models	Energetic electron and proton fluxes

Model Connections

Tutorials will cover:

- Model arguments, formulation, and included physical constraints
- Assimilated data
- Recent and planned improvements and upgrades
- Model operation and limitations

A (non-exhaustive) bibliography of other geospace empirical models

Name or Author	Model Output	Reference(s)
Lean	Atmosphere ozone column density	Lean, J. L. (2014), Evolution of Total Atmospheric Ozone from 1900 to 2100 Estimated with Statistical Models, J. Atmos. Sci., 71, 1956–1984.
NOEM	Lower thermosphere nitric oxide density	Marsh, D. R., S. C. Solomon, and A. E. Reynolds (2004), Empirical model of nitric oxide in the lower thermosphere, J. Geophys. Res., 109, A07301, doi:10.1029/2003JA010199.
DTM-2013	Thermosphere temperature, density, and composition	Bruinsma, S. L. (2015), The DTM-2013 thermosphere model, J. Space Weather Space Clim., 5, A1, doi:10.1051/swsc/2015001.
JB2008	Thermosphere mass density	Bowman, B. R., et al. (2008), A new empirical thermospheric density model JB2008 using new solar and geomagnetic indices, AIAA/AAS Astrodynamics Specialist Conference, 18–21 August 2008, Honolulu, Hawaii, paper AIAA 2008-6438.
Zoennchen	Exosphere hydrogen density	Zoennchen, J. H., U. Nass, and H. J. Fahr (2013), Exospheric hydrogen density distributions for equinox and summer solstice observed with TWINS1/2 during solar minimum, Ann. Geophys., 31, 513–527.
Mukhtarov	Ionosphere electron column density (total electron content)	Mukhtarov, P., D. Pancheva, B. Andonov, and L. Pashova (2013), Global TEC maps based on GNSS data: 1. Empirical background TEC model, J. Geophys. Res. Space Physics, 118, 4594–4608, doi:10.1002/jgra.50413.
Scherliess/ Fejer	Low-latitude Ionosphere plasma drifts	Scherliess, L., and B. G. Fejer (1999), Radar and satellite global equatorial F region vertical drift model, J. Geophys Res., 104, 6829–6842. Fejer, B. G., and L. Scherliess (1997), Empirical models of storm time equatorial zonal electric fields, J. Geophys Res., 102, 24,047–24,056.
Stening/ Winch	Ionosphere quiet-time electric currents	Stening R. J., and D. E. Winch (2013), The ionospheric Sq current system obtained by spherical harmonic analysis, J. Geophys. Res. Space Physics, 118, 1288–1297, doi:10.1002/jgra.50194.
Hardy	Ionosphere Conductivity, Auroral Power	Hardy, D. A., M. S. Gussenhoven, R. Raistrick, and W. J. McNeil (1987), Statistical and functional representations of the pattern of auroral energy flux, number flux, and conductivity, J. Geophys. Res., 92, 12,275–12,294.
Cousins	High-latitude electric potential	Cousins, E. D. P., and S. G. Shepherd (2010), A dynamical model of high-latitude convection derived from SuperDARN plasma drift measurements, J. Geophys Res., 115, A12329, doi:10.1029/2010JA016017.

A (non-exhaustive) bibliography of other geospace empirical models (continued)

Name or Author	Model Output	Reference(s)
Newell	Auroral Power and Probability	Newell, P. T., T. Sotirelis, and S. Wing (2010), Seasonal variations in diffuse, monoenergetic, and broadband aurora, J. Geophys. Res., 115, A03216, doi:10.1029/2009JA014805.
Papitashvili	Field-aligned Currents	Papitashvili, V. O., F. Christiansen, and T. Neubert (2002), A new model of field-aligned currents derived from high-precision satellite magnetic field data, Geophys. Res. Lett., 29, 1683, doi:10.1029/2001GL014207.
Cosgrove	Poynting Flux	Cosgrove, R. B., et al. (2014), Empirical model of Poynting flux derived from FAST data and a cusp signature, J. Geophys. Res. Space Physics, 119, 411–430, doi:10.1002/2013JA019105.
Sheeley	Plasmasphere Plasma Density	Sheeley, B. W., M. B. Moldwin, H. K. Rassoul, and R. R. Anderson (2001), An empirical plasmasphere and trough density model: CRRES observations, J. Geophys. Res., 106, 25,631-25,641.
Brautigam-Albert	Radiation Belt Radial Diffusion Coefficients	Brautigam, D. H., and J. M. Albert (2000), Radial diffusion analysis of outer radiation belt electrons during the October 9, 1990, magnetic storm, J. Geophys. Res., 105(A1), 291-309.
Ozeke	Radiation Belt Radial Diffusion Coefficients	Ozeke, L. G., I. R. Mann, K. R. Murphy, I. Jonathan Rae, and D. K. Milling (2014), Analytic expressions for ULF wave radiation belt radial diffusion coefficients, J. Geophys. Res. Space Physics, 119, 1587-1605, doi:10.1002/2013JA019204.
Weigel	Ground-level Magnetic Field Perturbations	Weigel, R. S., A. J. Klimas, and D. Vassiliadis (2003), Solar wind coupling to and predictability of ground magnetic fields and their time derivatives, J. Geophys. Res., 108(A7), 1298, doi:10.1029/2002JA009627.
Tsyganenko	Magnetosphere Magnetic Field	Tsyganenko, N. A., and M. I. Sitnov (2005), Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms, J. Geophys. Res., 110, A03208, doi:10.1029/2004JA010798.
Olson-Pfitzer Quiet	Magnetosphere Magnetic Field	W.P. Olson, K.A. Pfitzer, Magnetospheric magnetic field modeling, Annual Scientific Report, Air Force Office of Scientific Research contract F44620-75-C-0033, McDonnell Douglas Astronautics Co., Huntington Beach, CA, 1977.
Shue	Magnetopause Location	Shue, J.-H., et al. (1998), Magnetopause location under extreme solar wind conditions, J. Geophys. Res., 103, 17,691.