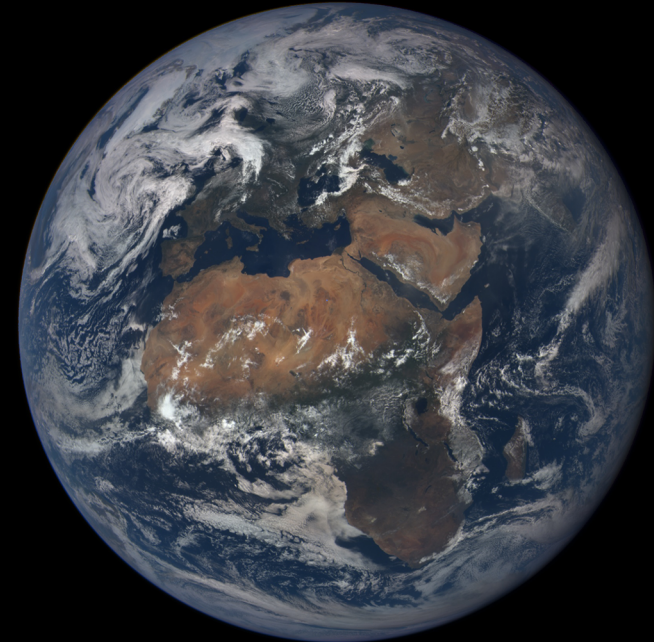


Earth Science / Exoplanet Synergies



Richard Eckman, Program Manager,
NASA Earth Science,
Atmospheric Composition, Exoplanet Research Programs

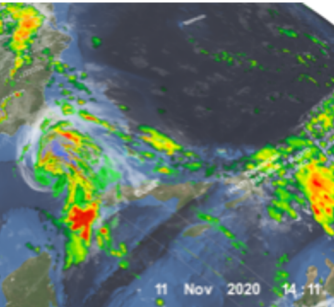
Nancy Y. Kiang, NASA Goddard Institute for Space Studies

Exoplanet Exploration Program Analysis Group (ExoPAG)
January 5, 2020

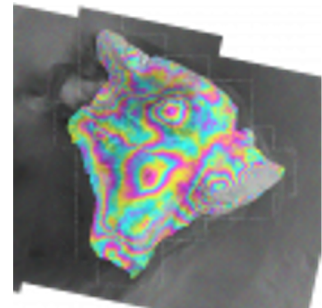
NASA Earth Science Focus Areas



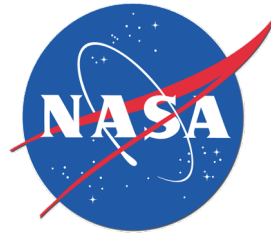
- Atmospheric Composition (AC)



- Weather and Atmospheric Dynamics



- Earth Surface and Interior



Earth Science Sub-Programs & Managers:

Physical Oceanography (CVC) -
Nadya Vinogradova-Shiffer

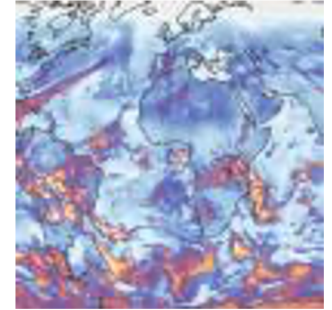
Ocean Biology & Biogeochemistry (CCE) - Laura Lorenzoni

Cryospheric Science (CVC) -
Thorsten Markus

Atmospheric Composition Modeling & Analysis (AC)

- Richard Eckman

- Climate Variability and Change (CVC)



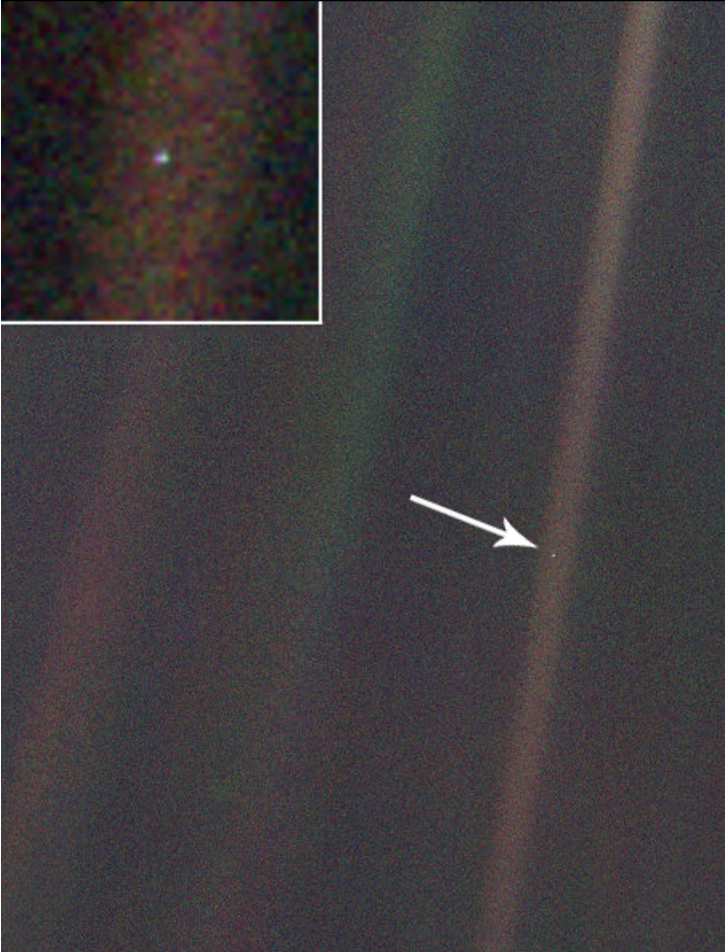
- Water and Energy Cycle



- Carbon Cycle and Ecosystems (CCE)



Earth as an Exoplanet: Remote Observation



Missions

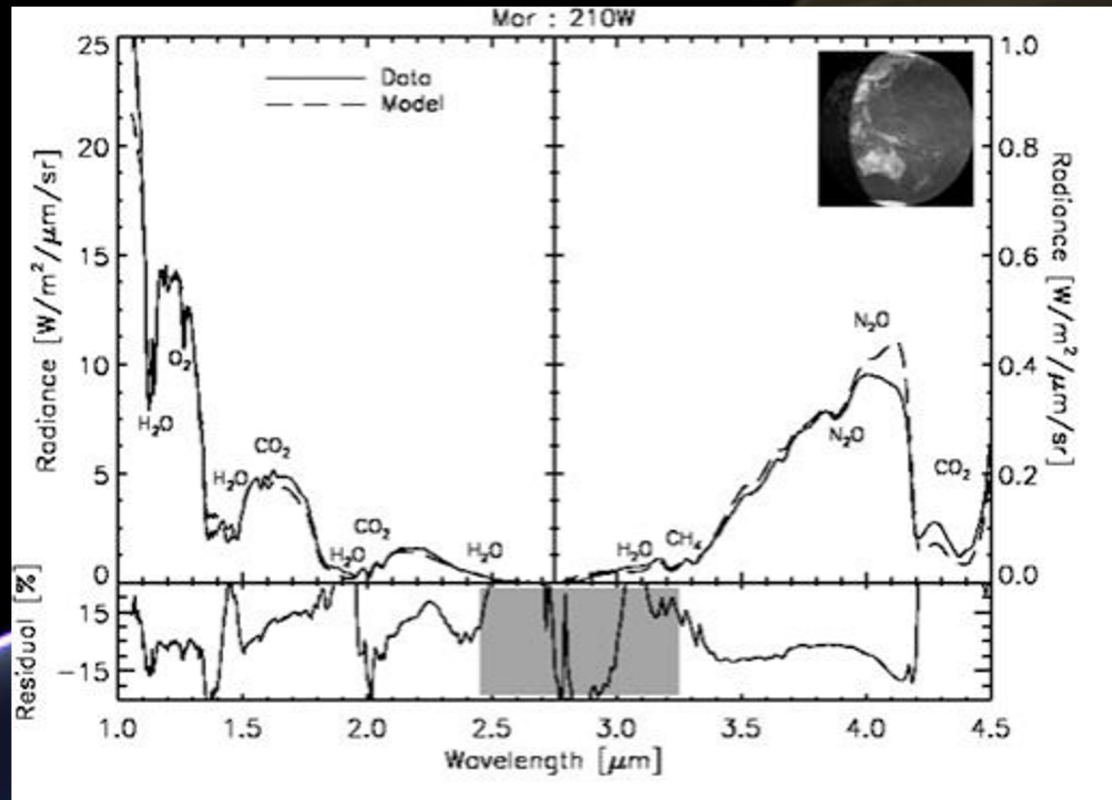
Galileo

Cassini-Huygens

EPOXI

DSCOVR

Earth as an Exoplanet: Remote Observation



Missions

Galileo

Cassini-Huygens

EPOXI

DSCOVR

Earthshine from Moon

Ground telescopes

Robinson et al., (2011) DOI: 10.1089/ast.2011.0642. Using EPOXI data.

Earth as an Exoplanet:

NASA EARTH FLEET

OPERATING & FUTURE THROUGH 2023



Earth as an Exoplanet: Earth Through Time

Geobiology / Geochemistry

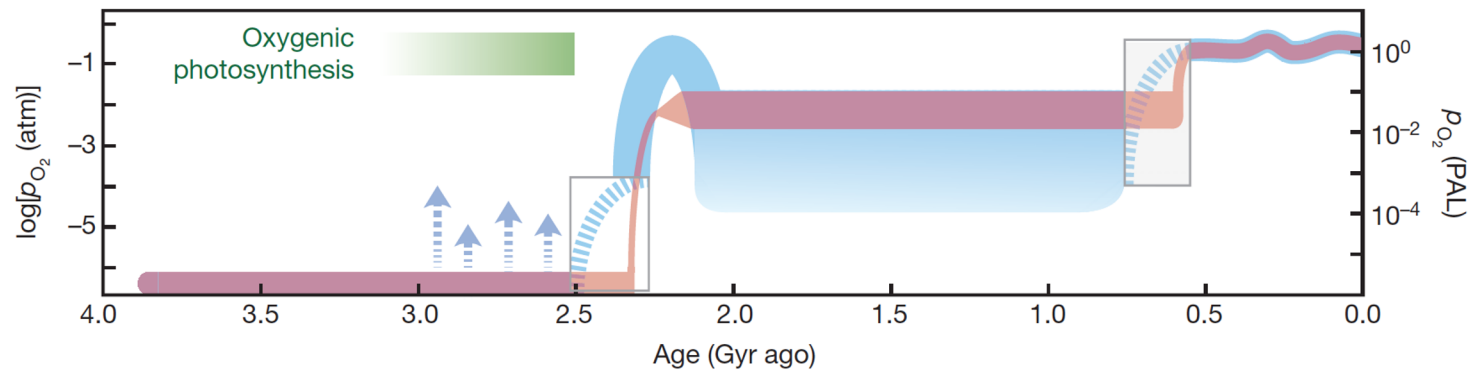


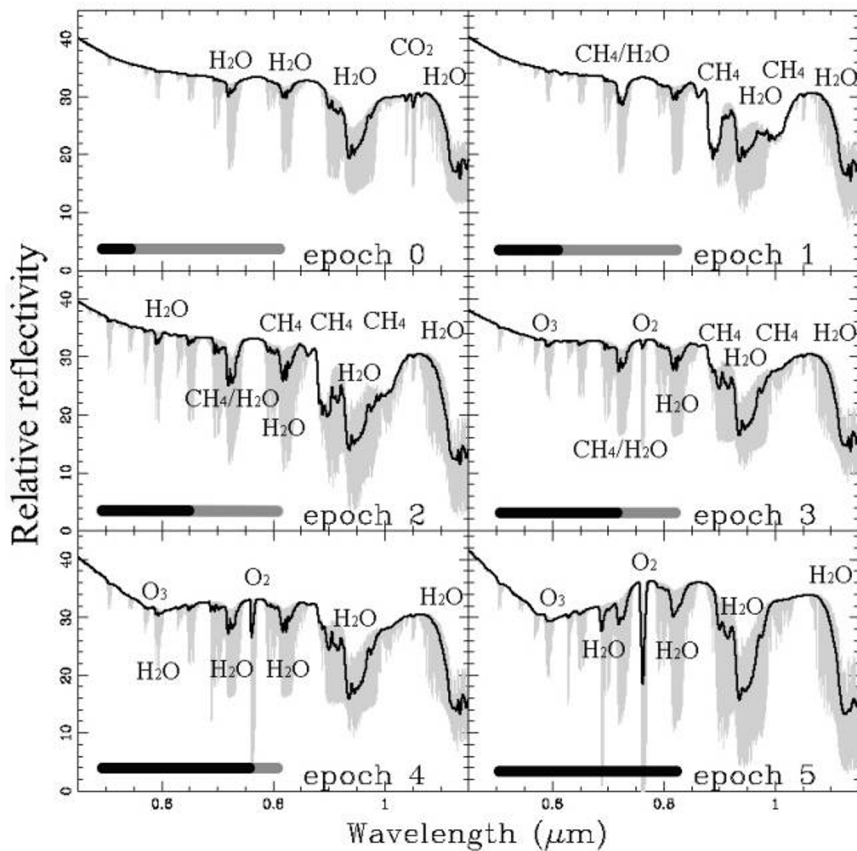
Figure 1 | Evolution of Earth's atmospheric oxygen content through time. The faded red curve shows a 'classical, two-step' view of atmospheric evolution⁹⁵, while the blue curve shows the emerging model (p_{O_2} , atmospheric partial pressure of O_2). Right axis, p_{O_2} relative to the present atmospheric level (PAL); left axis, $\log p_{O_2}$. Arrows denote possible 'whiffs' of O_2 late in the Archaean; their duration and magnitude are poorly understood. An additional

frontier lies in reconstructing the detailed fabric of 'state changes' in atmospheric p_{O_2} , such as occurred at the transitions from the late part of the Archaean to the early Proterozoic and from the late Proterozoic to the early Phanerozoic (blue boxes). Values for the Phanerozoic are taken from refs 96 and 97.

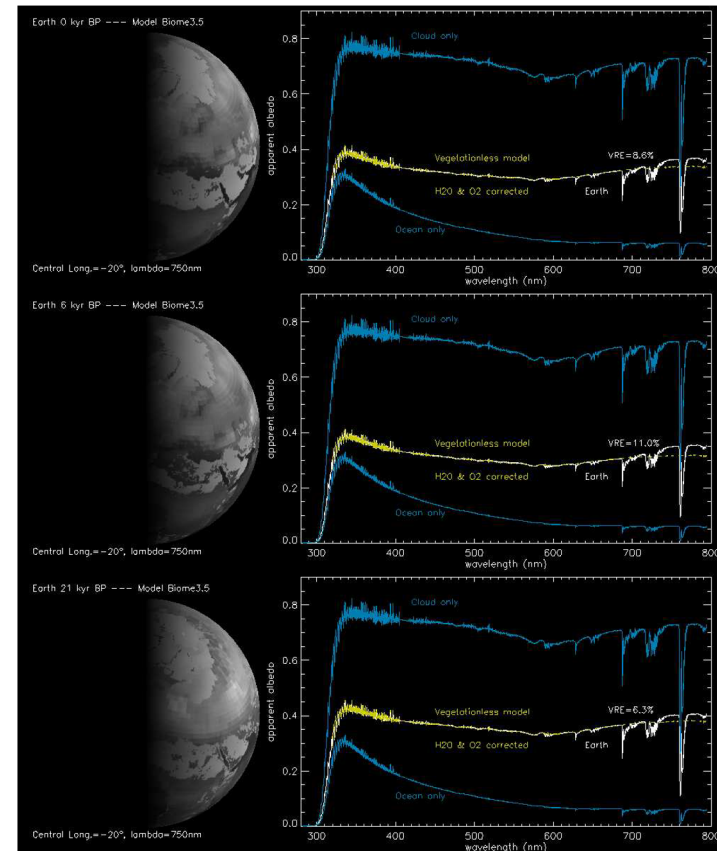
Lyons et al. (2014) doi:10.1038/nature13068

Earth as an Exoplanet: Earth Through Time

Kaltenegger et al. (2007). "Spectral evolution of an Earth-like planet." ApJ 658.

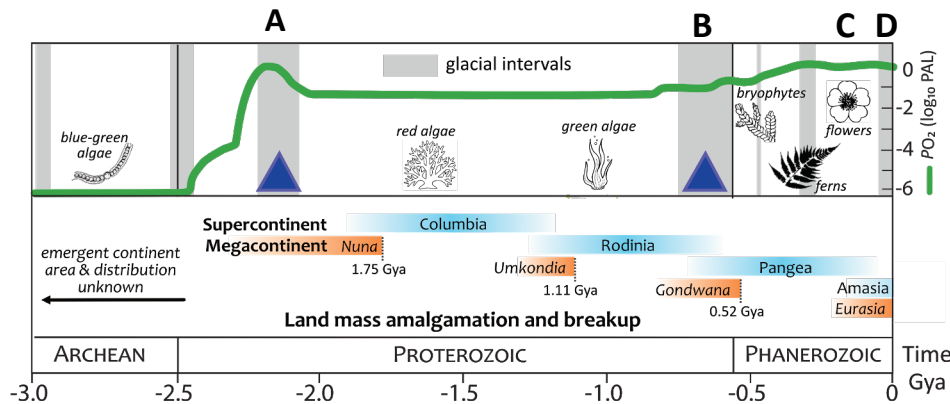
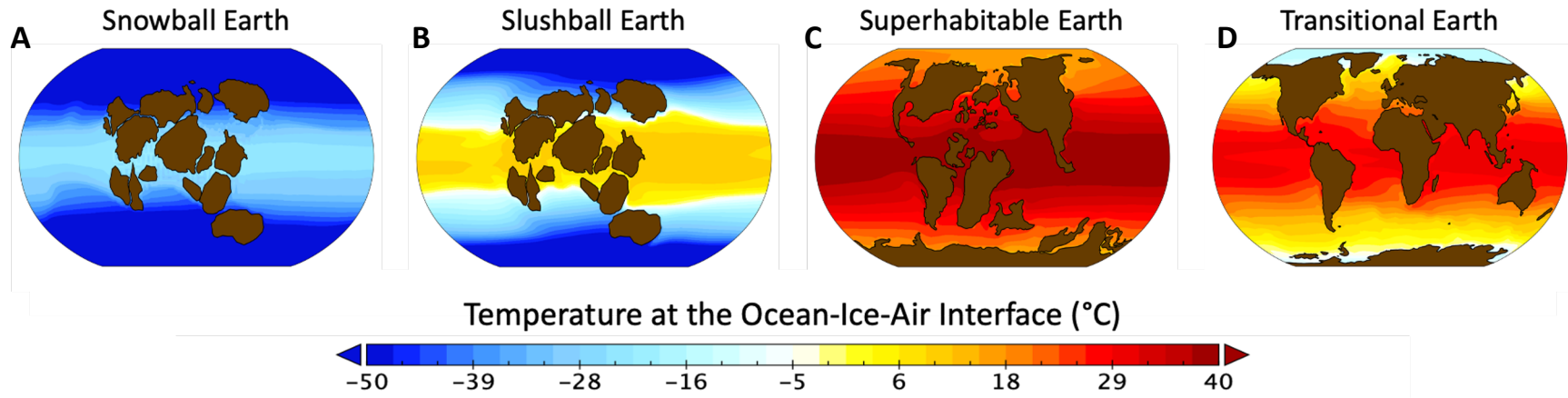


Arnold (2009). "The Earth as an extrasolar planet: The vegetation spectral signature today and during the last Quaternary climatic extrema," Intl J Astr, 8(2):81-94.



Earth as an Exoplanet: Earth Through Time

Paleoclimate in a Planetary Systems Context



Paleoclimate simulations A-D (above) correspond to A-D intervals noted at top of timeline chart (left).

Earth as an Exoplanet: Earth Through Time

Earth Interior in a Planetary Systems Context

THE ASTROPHYSICAL JOURNAL, 755:132 (11pp), 2012 August 20
© 2012. The American Astronomical Society. All rights reserved. Printed in the U.S.A.

doi:10.1088/0004-637X/755/2/132

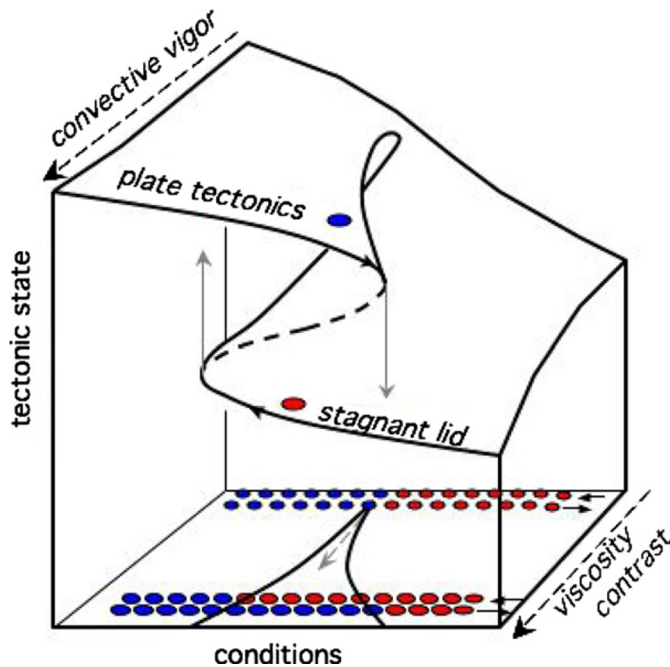
ON THE NOTION OF WELL-DEFINED TECTONIC REGIMES FOR TERRESTRIAL PLANETS IN THIS SOLAR SYSTEM AND OTHERS

A. LENARDIC¹ AND J. W. CROWLEY²

¹ Department of Earth Science, Rice University, MS 126, P.O. Box 1892, Houston, TX 77251-1892, USA; ajns@rice.edu

² Department of Earth and Planetary Science, Harvard University, 20 Oxford St., Cambridge, MA 02138, USA; jwgcrowley@gmail.com

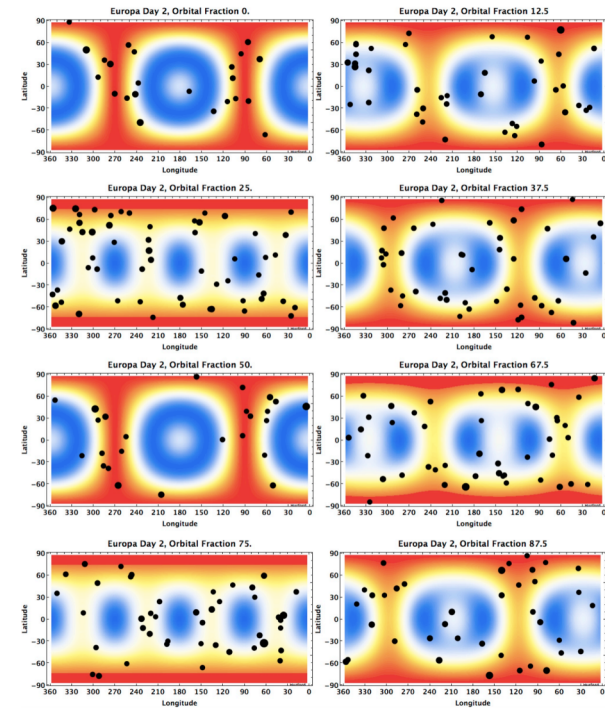
Received 2012 May 14; accepted 2012 June 10; published 2012 August 2



Icarus 338 (2020) 113466

Seismicity on tidally active solid-surface worlds

T.A. Hurford^{a,*}, W.G. Henning^{a,b}, R. Maguire^c, V. Lekic^c, N. Schmerr^c, M. Panning^d, V. J. Bray^e, M. Manga^f, S.A. Kattenhorn^g, L.C. Quick^a, A.R. Rhoden^{h,1}



Earth as an Exoplanet: Diversity of Life

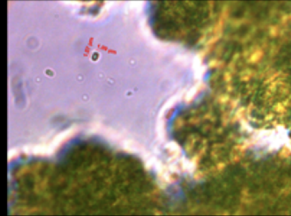


Earth as an Exoplanet: Diversity of Life

RADIATION INTERACTIONS



phototrophy
(light harvesting)

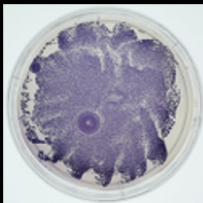


signaling bioluminescence

photoprotection
(sunscreen)



heat balance

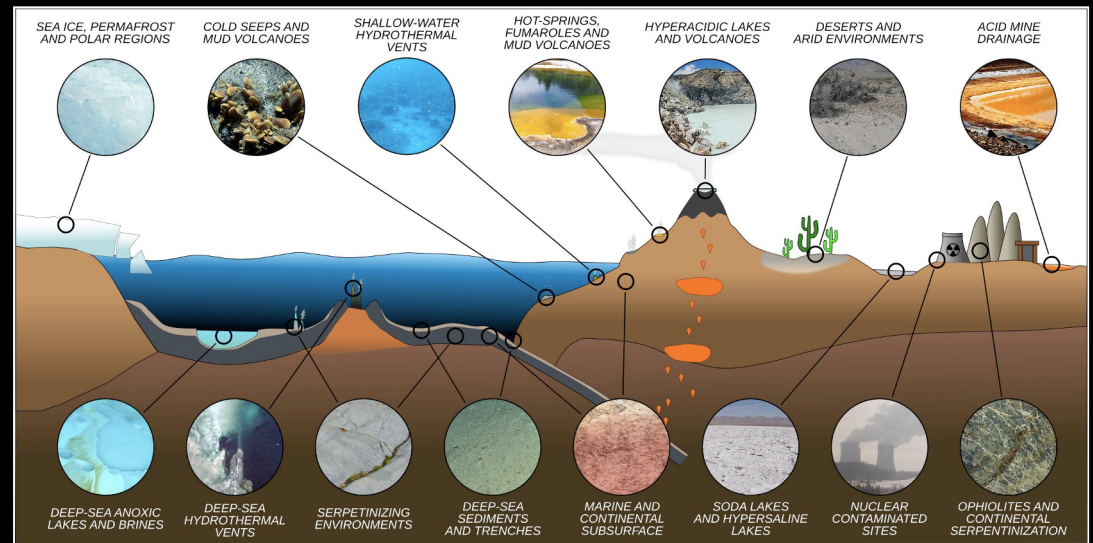


antibiotic defense



antioxidant

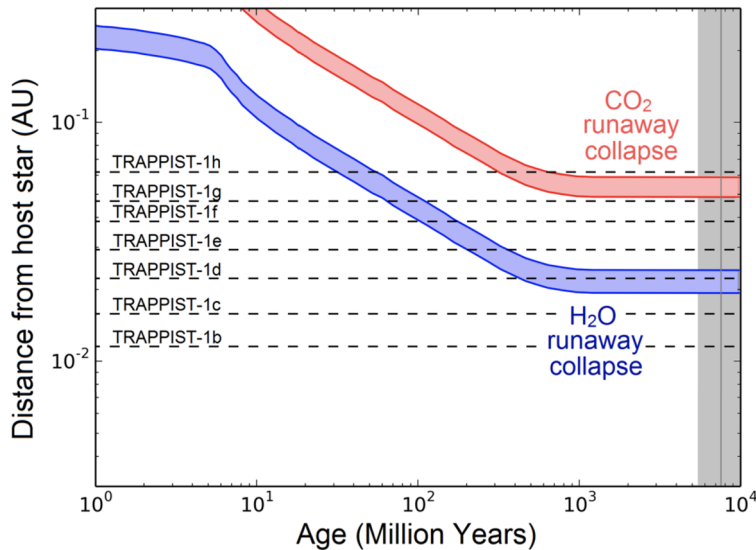
CLIMATE/CHEMISTRY METABOLISMS AND ADAPTATIONS



Merino et al. (2019) <https://doi.org/10.3389/fmicb.2019.00780>

Earth as an Exoplanet: Comparative Planetology

TRAPPIST-1 Planets Habitable Zones



Turbet et al. 2020. Space Sci Rev (2020) 216:100
<https://doi.org/10.1007/s11214-020-00719-1>

Proxima Centauri b as an: Aqua planet Earth continents Archean atmosphere(s)

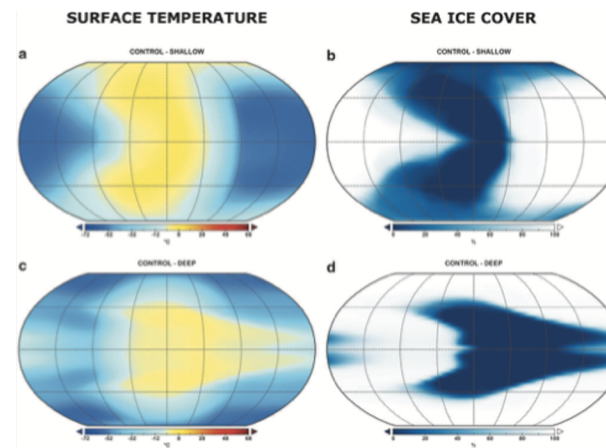
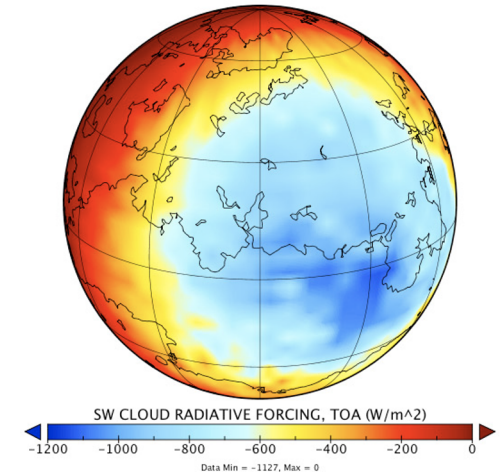


FIG. 8. (Left) surface temperature (°C) and (right) sea ice cover (%) for experiments (a, b) *Control-Shallow* and (c, d) *Control-Deep*.

Del Genio et al. 2019. DOI: 10.1089/ast.2017.1760

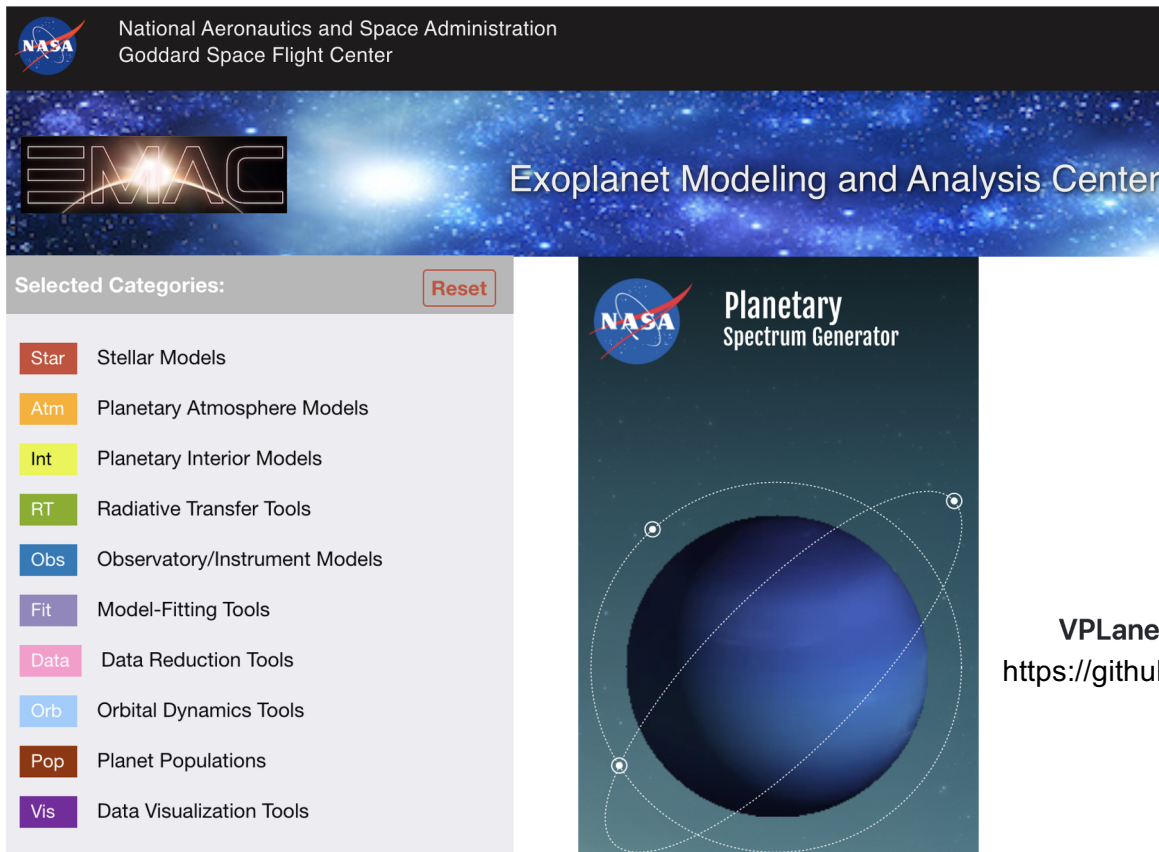
Early Venus

SHIELDING OF SUNLIGHT BY CLOUDS ON ANCIENT VENUS



Way et al. 2016. doi:10.1002/2016gl069790

Earth as an Exoplanet: Community Modeling Tools



National Aeronautics and Space Administration
Goddard Space Flight Center

EMAC Exoplanet Modeling and Analysis Center

Selected Categories: Reset

- Star Stellar Models
- Atm Planetary Atmosphere Models
- Int Planetary Interior Models
- RT Radiative Transfer Tools
- Obs Observatory/Instrument Models
- Fit Model-Fitting Tools
- Data Data Reduction Tools
- Orb Orbital Dynamics Tools
- Pop Planet Populations
- Vis Data Visualization Tools

Planetary Spectrum Generator

<https://psg.gsfc.nasa.gov/>



<https://www.giss.nasa.gov/projects/astrobio/>



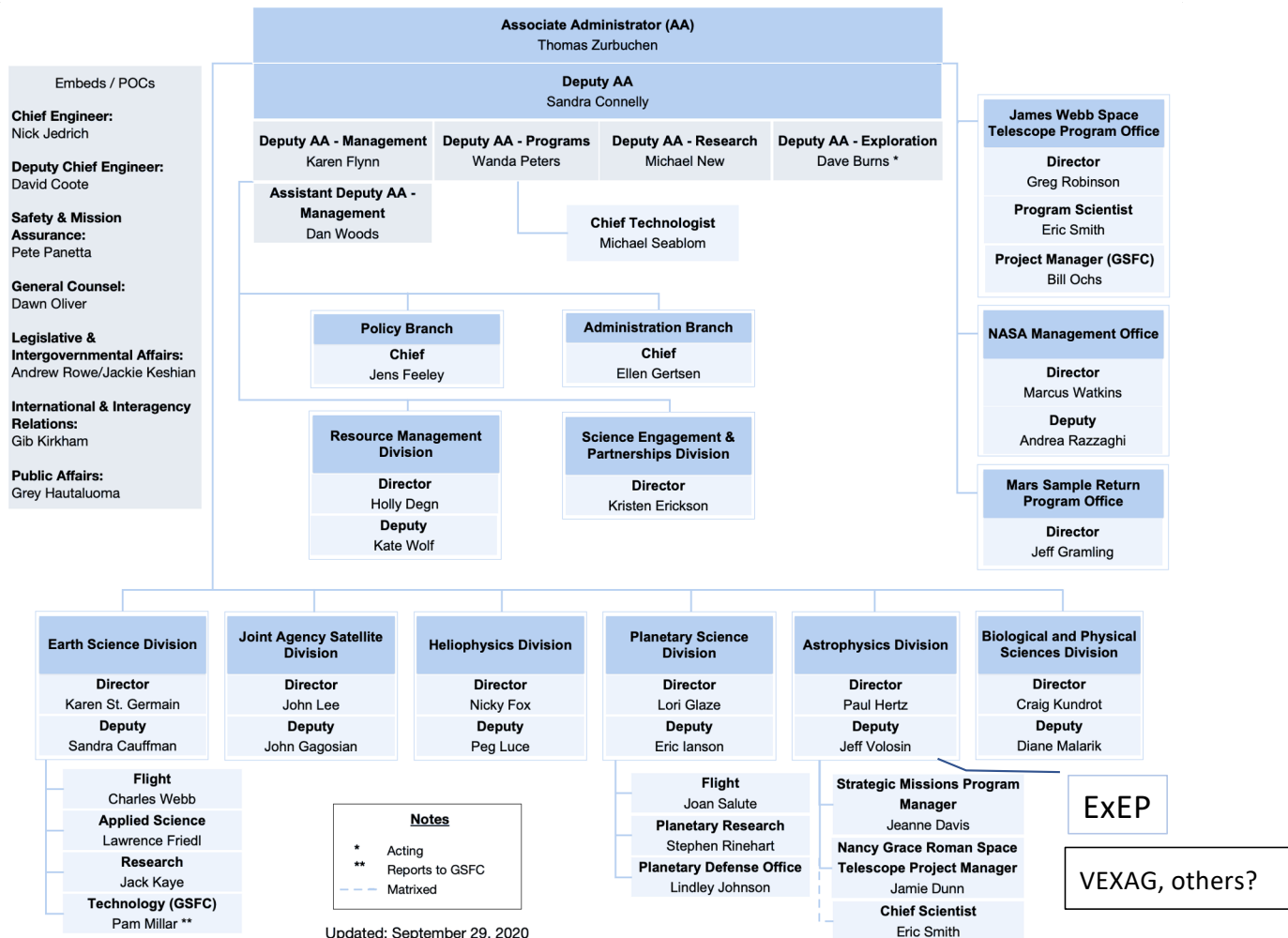
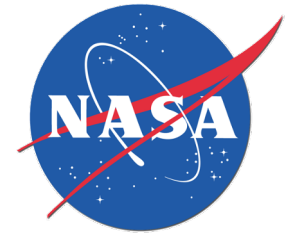
VPlanet: The Virtual Planet Simulator

<https://github.com/VirtualPlanetaryLaboratory/vplanet>

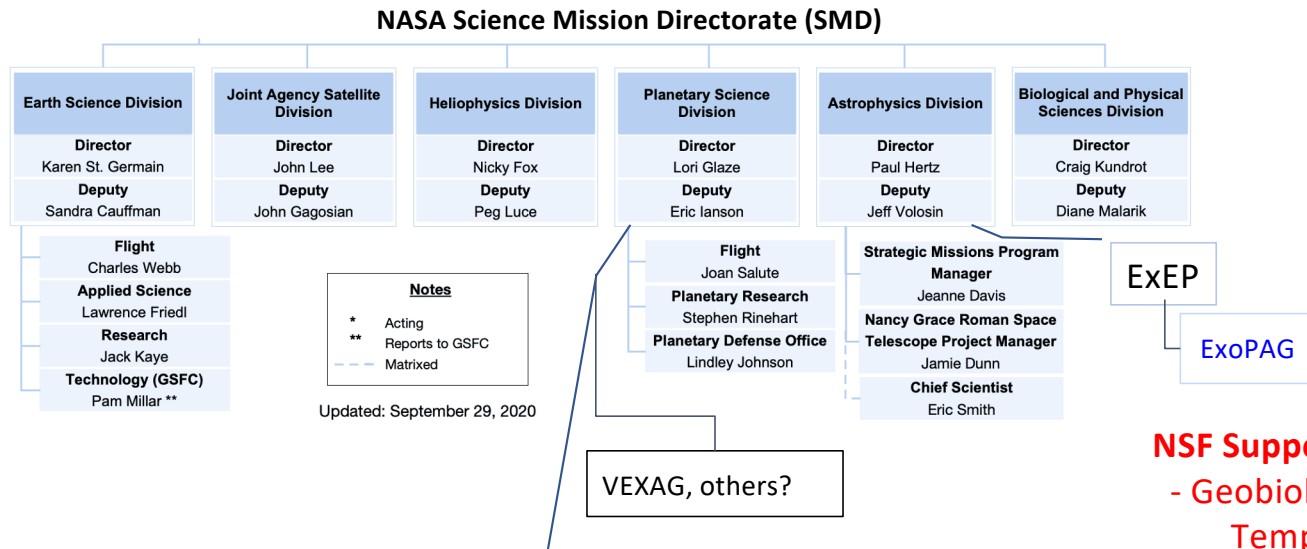
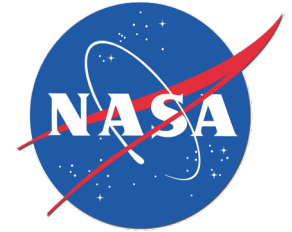


<https://www.cesm.ucar.edu/models/ccsm4.0/ccsm/>

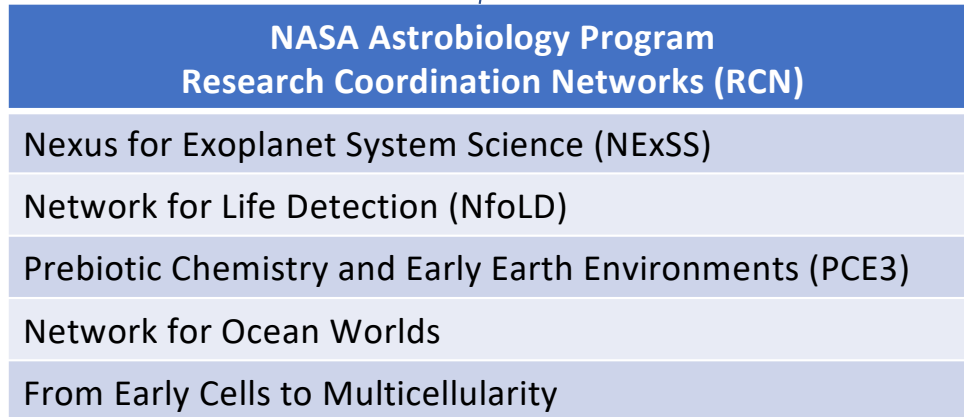
NASA Science Mission Directorate (SMD)



Organizational Support for Earth Science in Exoplanet Science



Jack Kaye used to support original Astrobiology Institute through Earth Science ~\$500K/yr



NSF Support

- Geobiology & Low Temperature Geochemistry
- Origin of Life
- Paleoclimate
- P2C2
- Sedimentary Geology & Paleobiology

USGS?

Private:

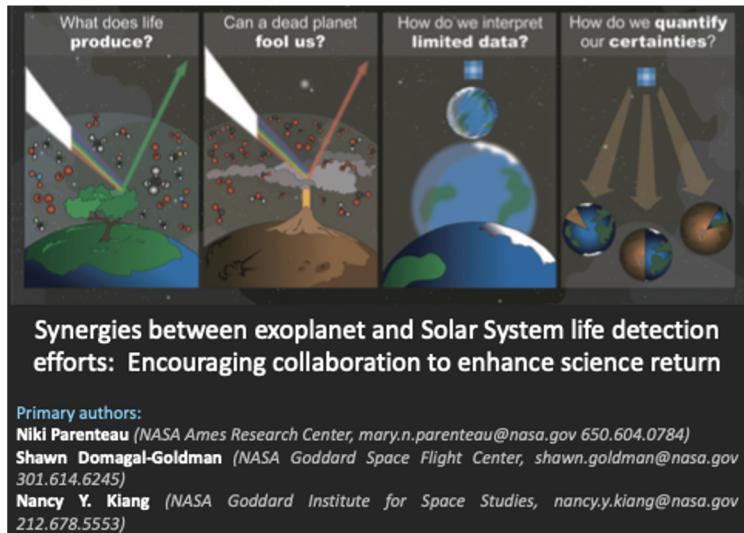
- Breakthrough Initiative
- Simons Foundation

NASA ROSES

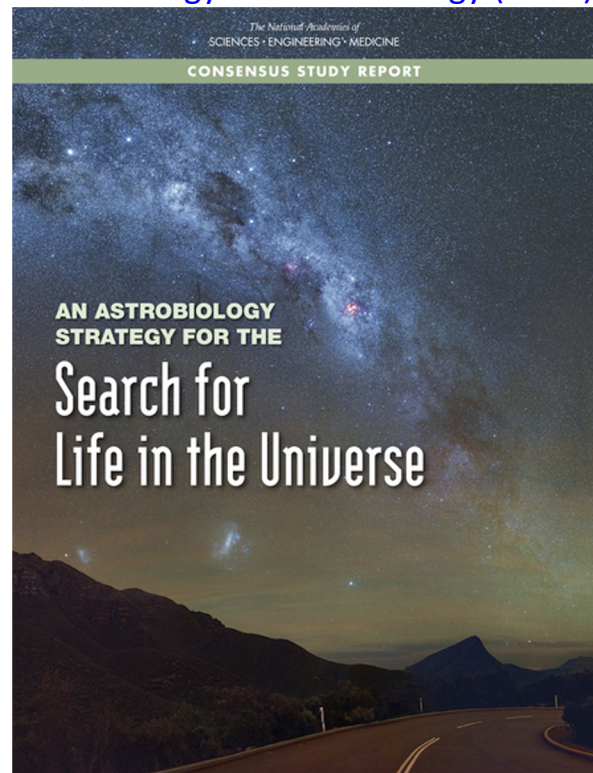
Program	Program Managers	Earth scientist participation
Exoplanet Research Program (XRP)	Astro, Planetary, Helio, Earth	remote sensing, lab kinetics
Habitable Worlds	Planetary, Helio	climate modeling, geophysics
Exobiology	Planetary	lab kinetics, microbiology, biogeosciences, biophysics
Solar Systems Workings (SSW)	Planetary	Moon and Solar System Planets, climate modeling, geology
Living With A Star	Helio	atmospheric chemistry
Lunar Data Analysis	Planetary	Earth history: terrestrial meteorites on the lunar surface
Emerging Worlds	Planetary	geophysics, petrology
Astrobiology ICAR	Planetary	biochemistry, evolutionary biology, microbial ecology, geophysics, petrology, geochemistry, astronomy, planetary science

National Research Council (NRC) Consensus Study Reports Interdisciplinary Decadal White Papers: Planetary, Astrobiology, Exoplanet, Earth Science

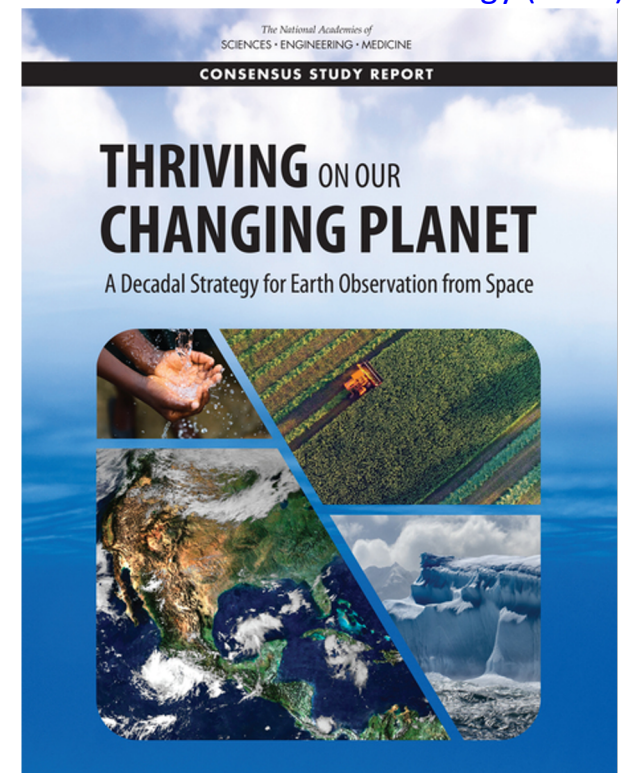
Exoplanet Science Strategy (2018)



Astrobiology Science Strategy (2018)



Earth Science Decadal Strategy (2017)



Earth vs. Exoplanet Conferences/Workshops

December: American Geophysical Union

January: Exoplanet Exploration Program Analysis Group (ExoPAG)

AAS

February: Habitable Worlds

April? June?: AbSciCon

June: ExoPAG

Others: ?

Discussion questions

- What Earth Science can be solicited to support exoplanet science and the search for life? What Earth Science is needed that is not directly observable for exoplanets?
- How can NASA better organize its Divisions and ROSES programs to support Exoplanet/Earth Science collaborations?
- What conferences/meetings/workshops should be targeted to foster exoplanet-Earth Science collaborations?