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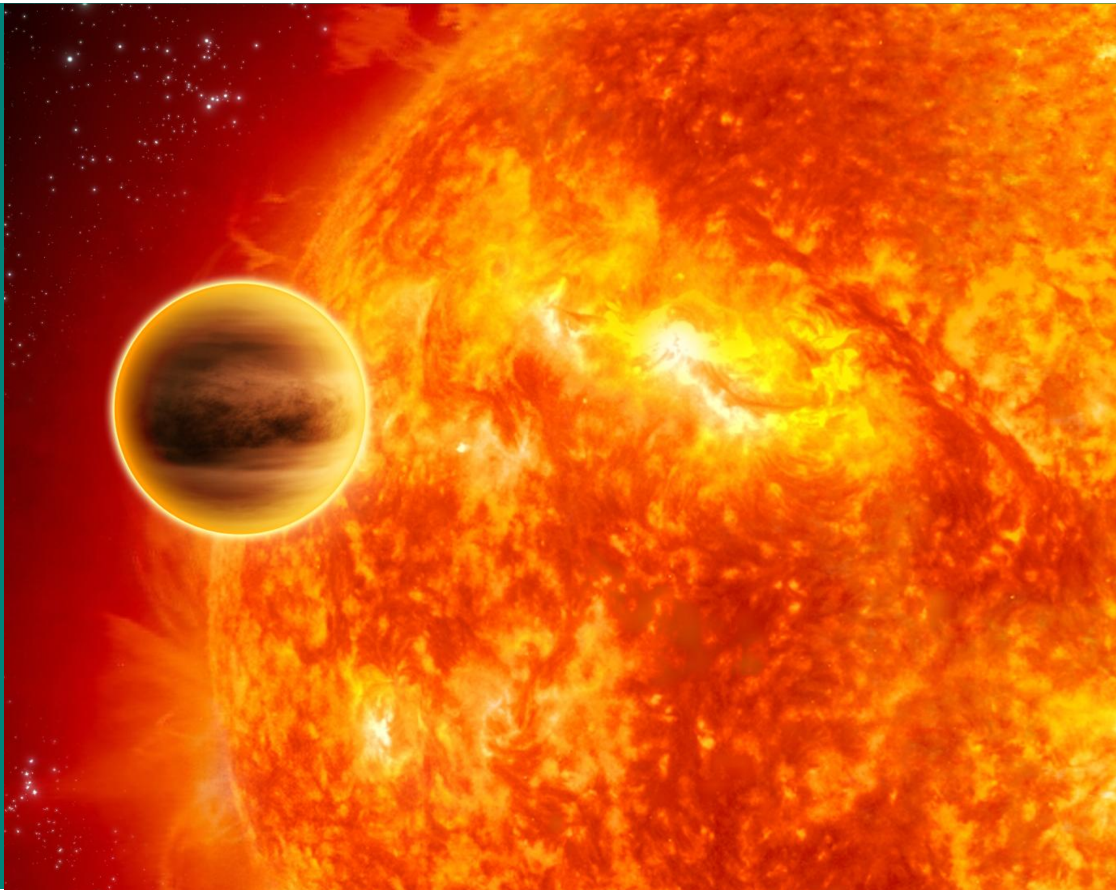
VIPER (*Versatile Interactive Planet simulator for Extrasolar Research*):

toward a universal model for planetary climate



Universität Hamburg
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Max-Planck-Institut für Meteorologie

Helmholtz-Zentrum Geesthacht
Zentrum für Material- und Küstenforschung

DKRZ
DEUTSCHES KLIMARECHENZENTRUM

University of Hamburg – Meteorological Group
Developments for (exo)planets climate mode

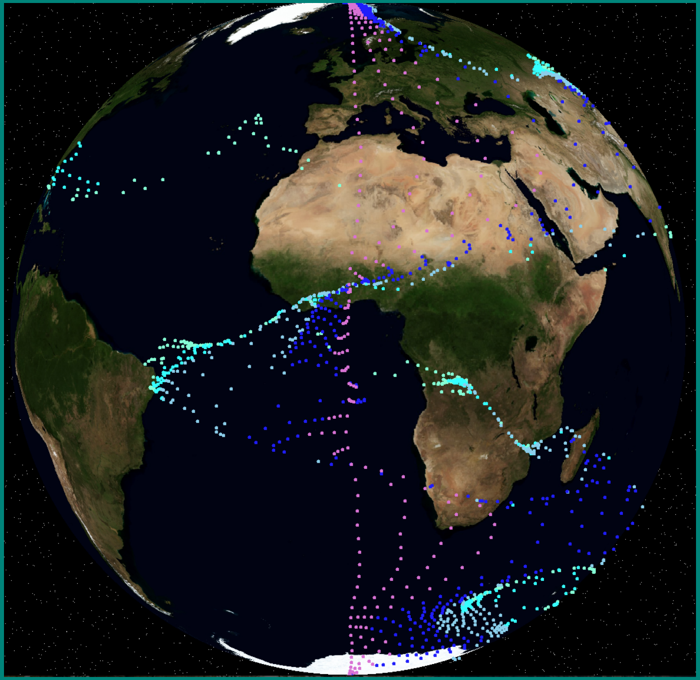
7/23/13

Nicolas Iro

Universität Hamburg

The Grindelberg Model Suite: Overview

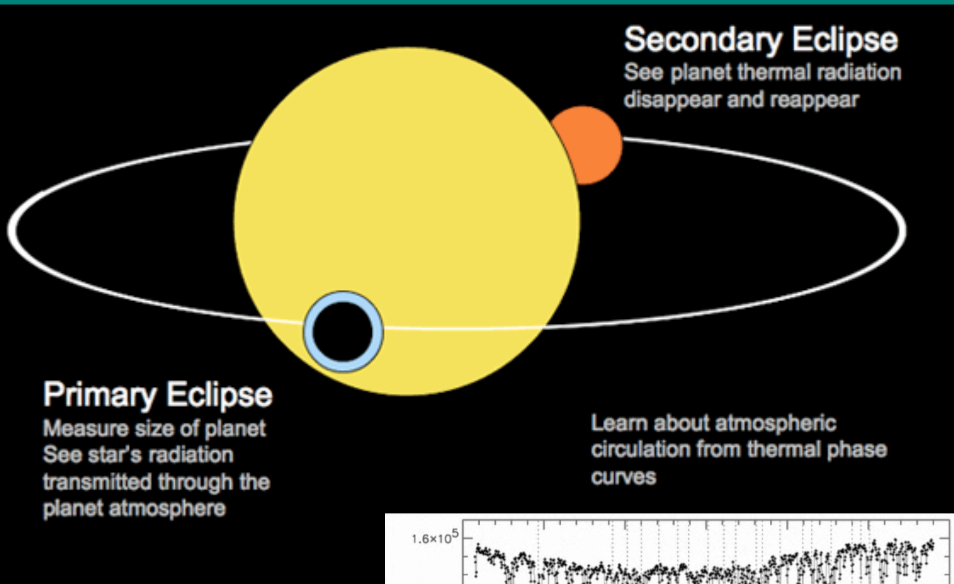
Nicolas Iro
Edilbert Kirk
Valerio Lucarini
Frank Lunkeit
Hartmut Borth
Salvatore Pascale

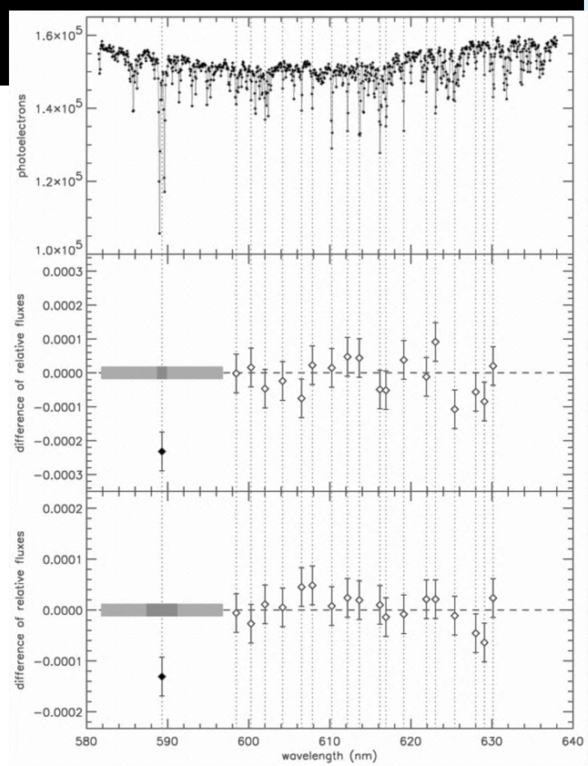


1. **Introduction**
2. **The model suite, current state**
    - Model of intermediate complexity
    - Some applications
3. **Coupling RT and hydrodynamics**
    - Newtonian cooling approximation
    - 2-band approximation
    - Band models
4. **Future developments**

Introduction

Observation of transits



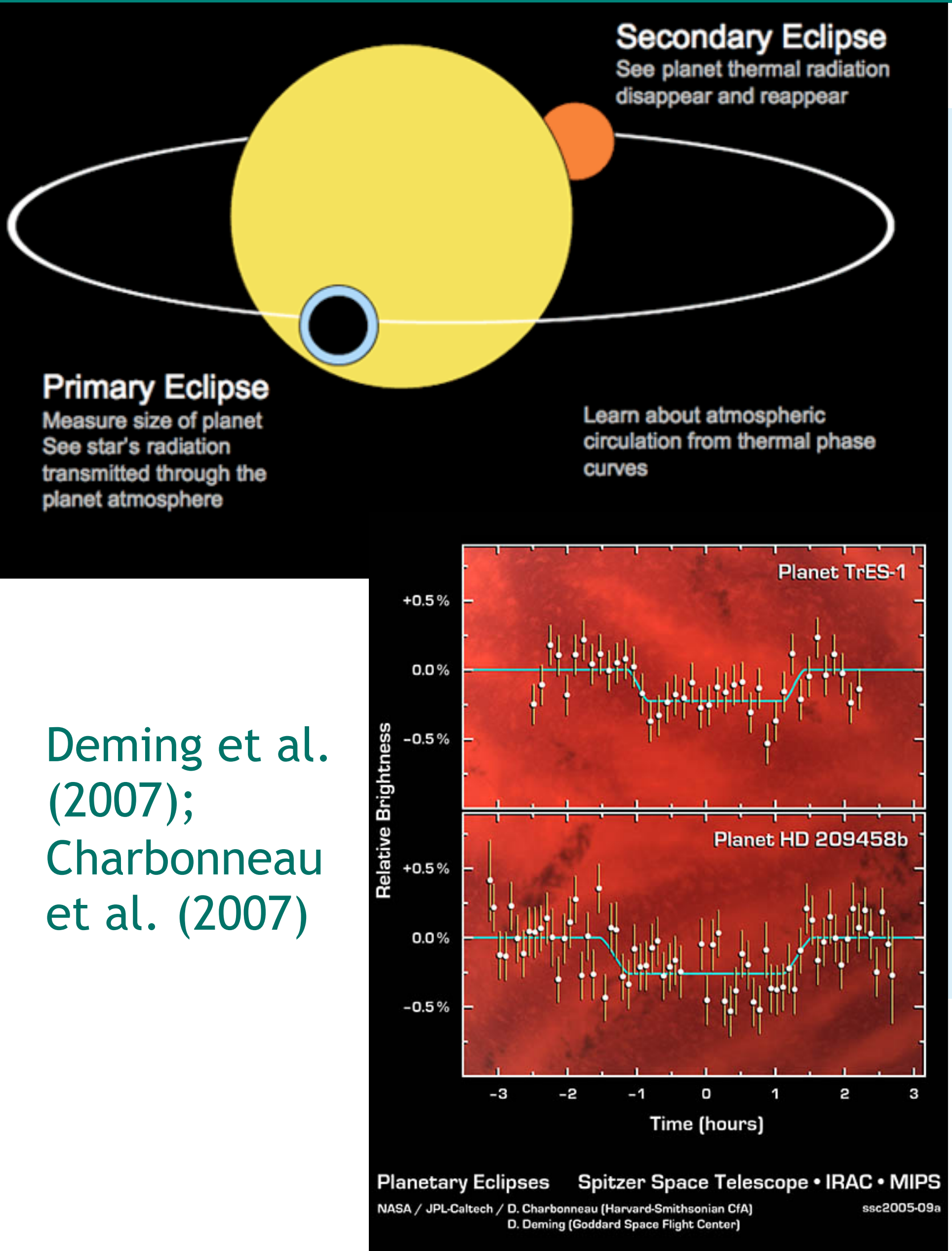


Charbonneau et al. (2002)

- Discovery of planet transiting its star:
  - New kind of information: accurate radius and mass, atmospheric temperature and composition
  - New questions: problem for models to explain observational constraints

Introduction

Observation of transits



Deming et al. (2007); Charbonneau et al. (2007)

- Discovery of planet transiting its star:
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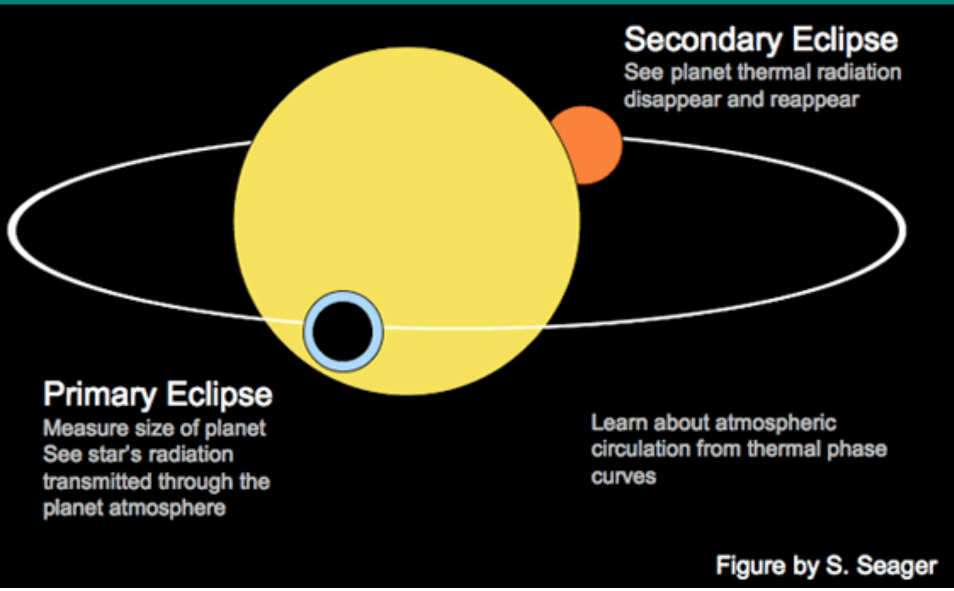
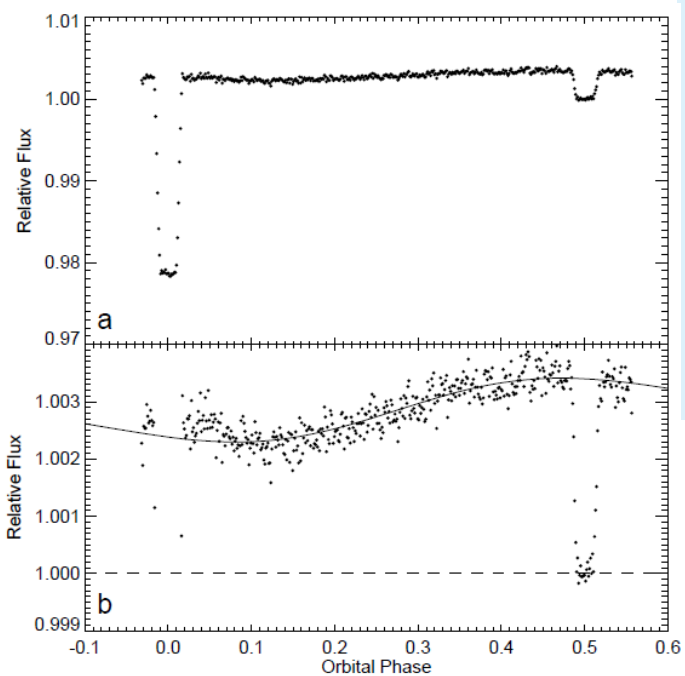
Observation of transits



Knutson et al. (2007)



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    - New kind of information: accurate radius and mass, atmospheric temperature and composition
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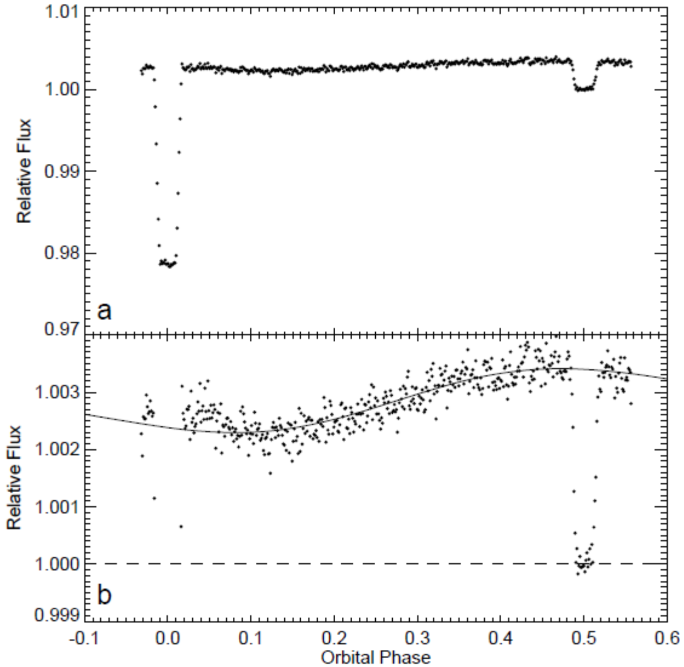
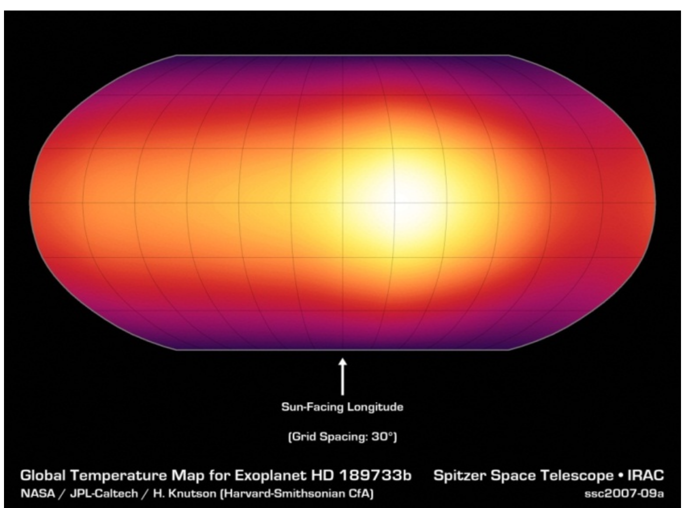
Introduction

Transiting planets





Transiting planets questions

- **Each type of observations: different location on planet**
- **Heat redistribution / Atmospheric dynamics: the planet is not 1d !!**

Knutson et al. (2007)

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Newtonian cooling approximation

2-band approximation

Band models

4. Future developments


ECHAM
ECHAM
PLASIM

Current model

Description

- **Planet simulator: PLASIM**

  •Dynamical core

  •Parameterization

  •Subsystems (humidity, clouds/ precipitation, …)

  •Graphical interface

Portable Univ. Model of the Atmosphere: PUMA

- Dynamical core only
- Boundary conditions
- Graphical interface

Key features

Portable	Linux, Unix, Mac OSX, Solaris and other Unix type systems.
Open source	All models are open source and use open source libraries only. (Xlib for graphics, NetCDF for data storage, MPI for parallel execution).
Modular	Problem dependent model configuration.
Scalable	Wide range of usable horizontal and vertical resolution.
Easy to use	Graphical ModelStarter for setup, compile & run. Graphical User Interface (GUI) for run control and views.
Documented	User‘s Guide, Reference Manual, commented FORTRAN code with references to literature and Manuals.
Parallel	The Message Passing Interface (MPI) is supported on multicore systems or clusters.
Fast	1 year PUMA T21 : 5 sec on iMac (4 cores Intel Core i5) 1 year PlaSim T21 : 90 sec on server node (2 x 4 cores Intel Xeon)
Compatible	Includes postprocessor for writing NetCDF gridded data, COADS, ECHAM, CDO, Grads, and Ferret compatible.
Support	Forum, eMail support, reference simulation
User base	Ca. 50 international Universities and Research Institutions

Primitive Equations

Conservation of momentum (vorticity and divergence equation)

$$\frac{\partial \zeta + f}{\partial t} = \frac{1}{(1-\mu^2)}\frac{\partial F_\nu}{\partial \lambda} - \frac{\partial F_u}{\partial \mu} + P_\zeta$$

$$\frac{\partial D}{\partial t} = \frac{1}{(1-\mu^2)}\frac{\partial F_u}{\partial \lambda} + \frac{\partial F_\nu}{\partial \mu} - \nabla^2 E - \nabla^2(\phi + T_0 \ln p_s) + P_D$$

Hydrostatic approximation (using the equation of state)

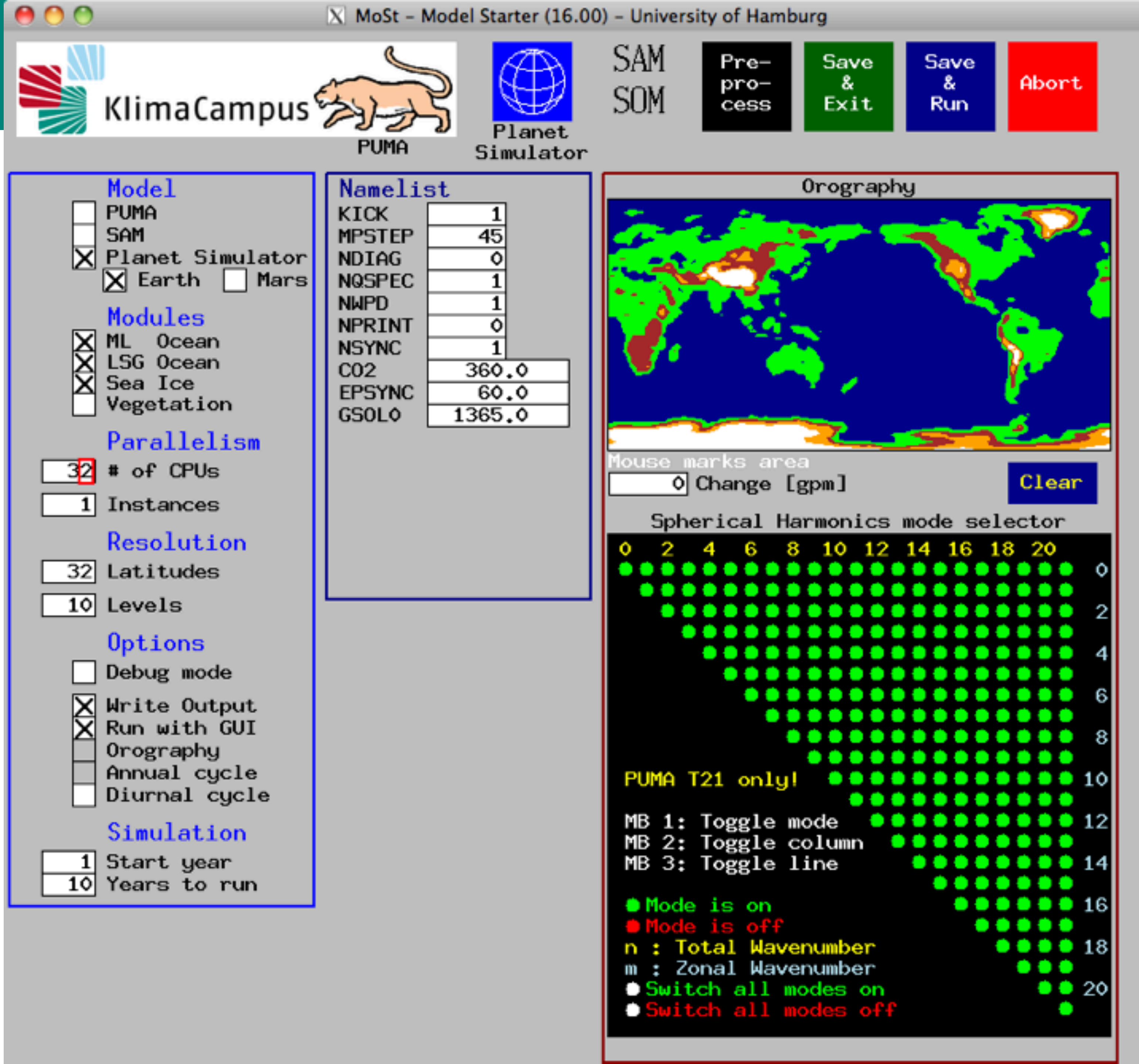
$$0 = \frac{\partial \phi}{\partial \ln \sigma} + T$$

Conservation of mass (continuity equation)

$$\frac{\partial \ln p_s}{\partial t} = -\int_0^1 A d\sigma$$

Thermodynamic equation

$$\frac{\partial T'}{\partial t} = F_T - \dot{\sigma}\frac{\partial T}{\partial \sigma} + \kappa W T + \frac{J}{c_p} + P_T$$


MoSt - Model Starter (16.00) - University of Hamburg
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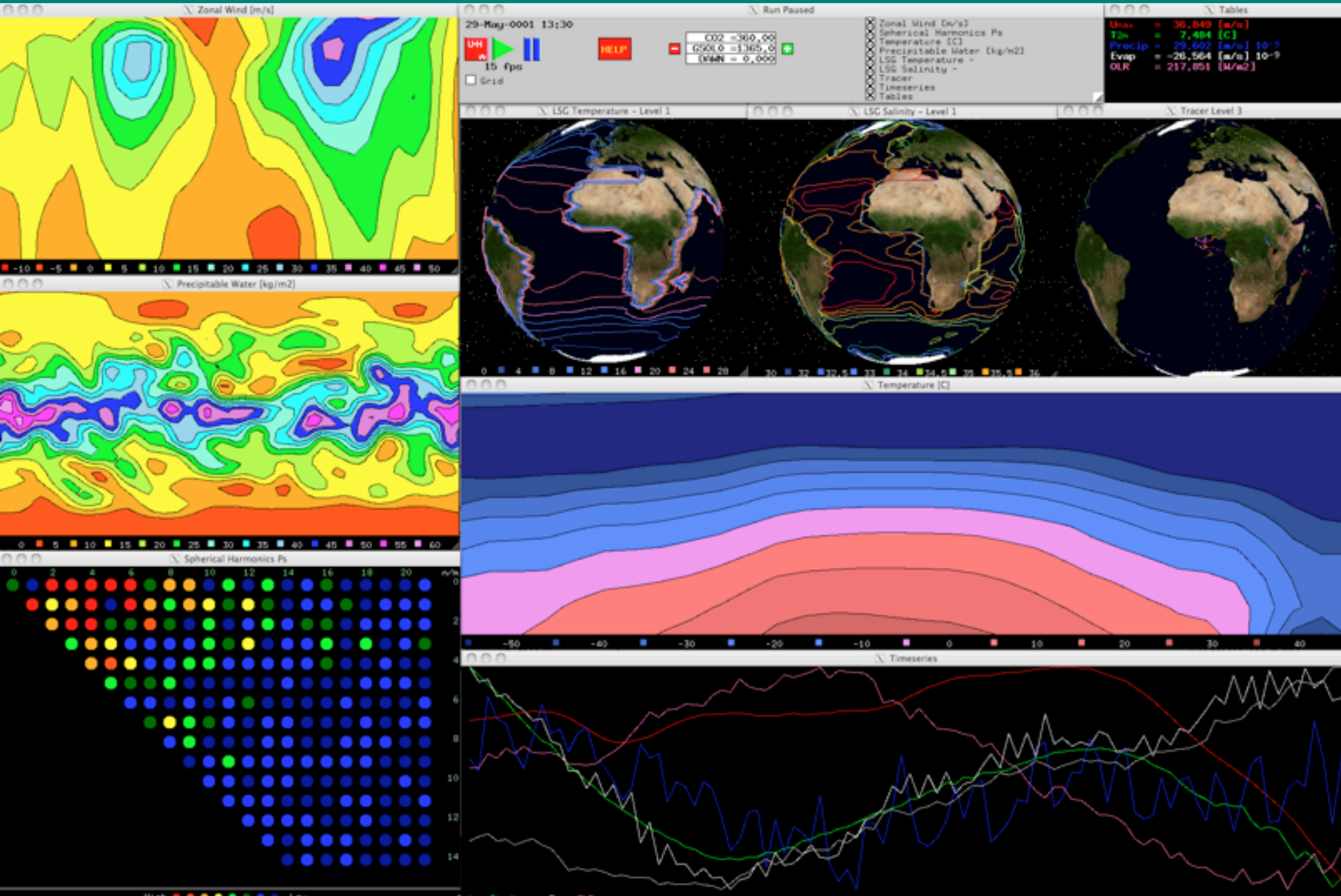
PUMA
Planet Simulator
SAM
SOM
Pre-process
Save & Exit
Save & Run
Abort
Model
PUMA
SAM
Planet Simulator
Earth
Mars
Modules
ML Ocean
LSG Ocean
Sea Ice
Vegetation
Parallelism
32 # of CPUs
1 Instances
Resolution
32 Latitudes
10 Levels
Options
Debug mode
Write Output
Run with GUI
Orography
Annual cycle
Diurnal cycle
Simulation
1 Start year
10 Years to run
Namelist
KICK 1
MPSTEP 45
NDIAG 0
NQSPEC 1
NWPD 1
NPRINT 0
NSYNC 1
CO2 360.0
EPSYNC 60.0
GSOL0 1365.0
Orography
Mouse marks area
0 Change [gpm]
Clear
Spherical Harmonics mode selector
0 2 4 6 8 10 12 14 16 18 20
PUMA T21 only!
MB 1: Toggle mode
MB 2: Toggle column
MB 3: Toggle line
Mode is on
Mode is off
n : Total Wavenumber
m : Zonal Wavenumber
Switch all modes on
Switch all modes off

aCampus


Zonal Wind [m/s]
Run Paused
Tables
29-May-0001 13:30
15 fps
Grid
HELP
CO2 =360.00
GSOL0 =1365.0
Zonal Wind [m/s]
Spherical Harmonics Ps
Temperature [C]
Precipitable Water [kg/m2]
LSG Temperature -
LSG Salinity -
Tracer
Timeseries
Tables
Umax = 36.849 [m/s]
T2m = 7.484 [C]
Precip = 29.602 [m/s] 10-9
Evap = -26.564 [m/s] 10-9
OLR = 217.851 [W/m2]
LSG Temperature - Level 1
LSG Salinity - Level 1
Tracer Level 3
Precipitable Water [kg/m2]
Temperature [C]
Spherical Harmonics Ps
Timeseries
High
Low
Umax T2m Precip Evap OLR

Requirements

- Hardware

  Any from Netbook (has run on Raspberry PI) to massive parallel cluster

- Software

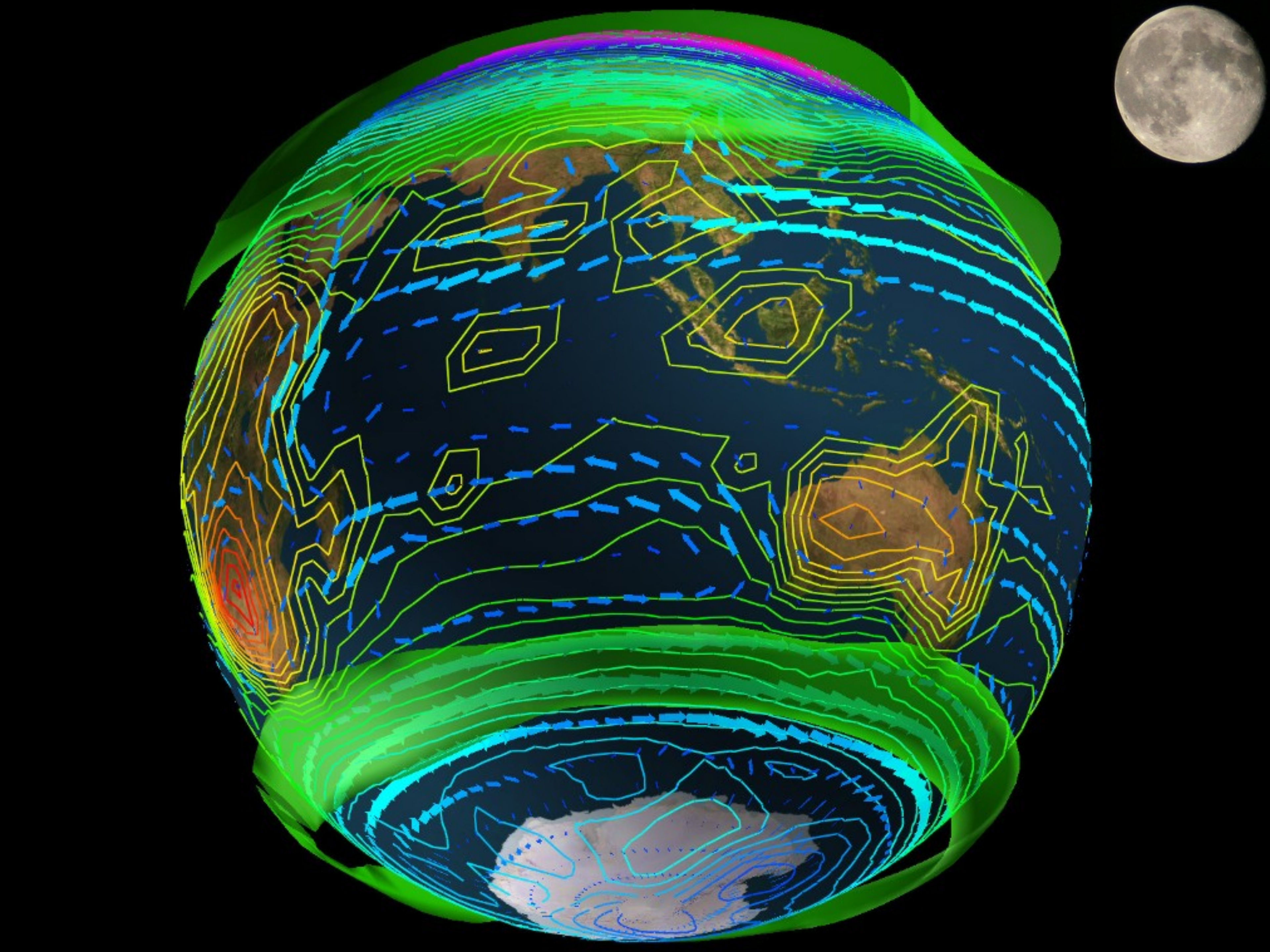
  Linux, Mac OSX, or any UNIX like operating system

  (or in a virtual machine on a Windows-host)

  FORTRAN-90 Compiler (gfortran or other)

  Xlib development package (<include> files)

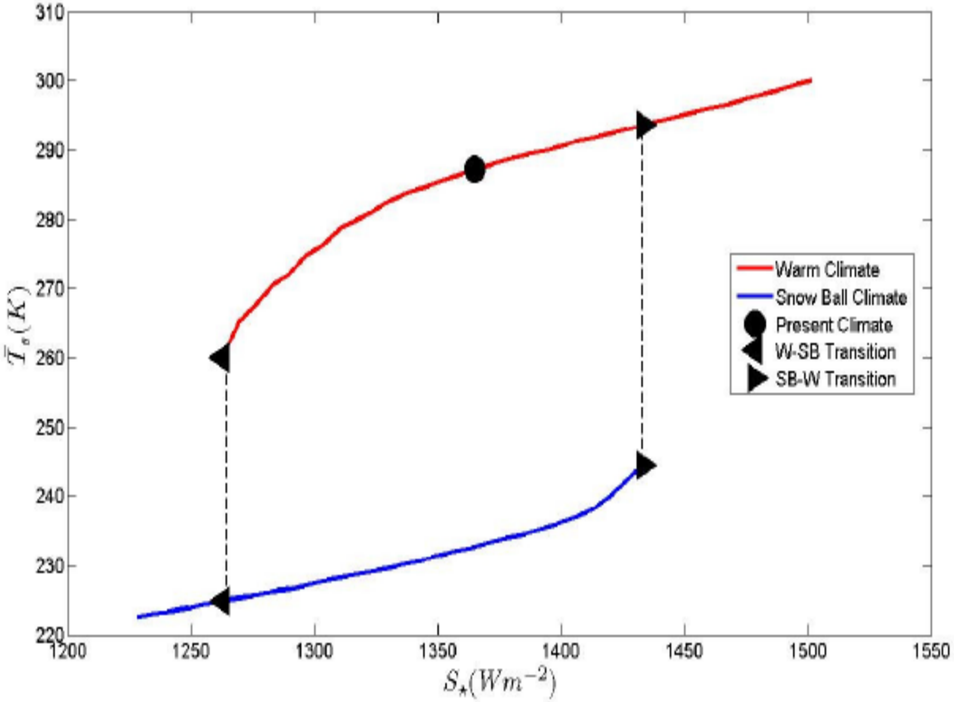
  NetCDF library (for data processing)



Current model

Applications

- Application to Earth



Lucarini et al. (QJRMS, 2010)

- **PLASIM**
- Hysteresis experiment
- Thermodynamical diagnostics built-in (entropy, …)

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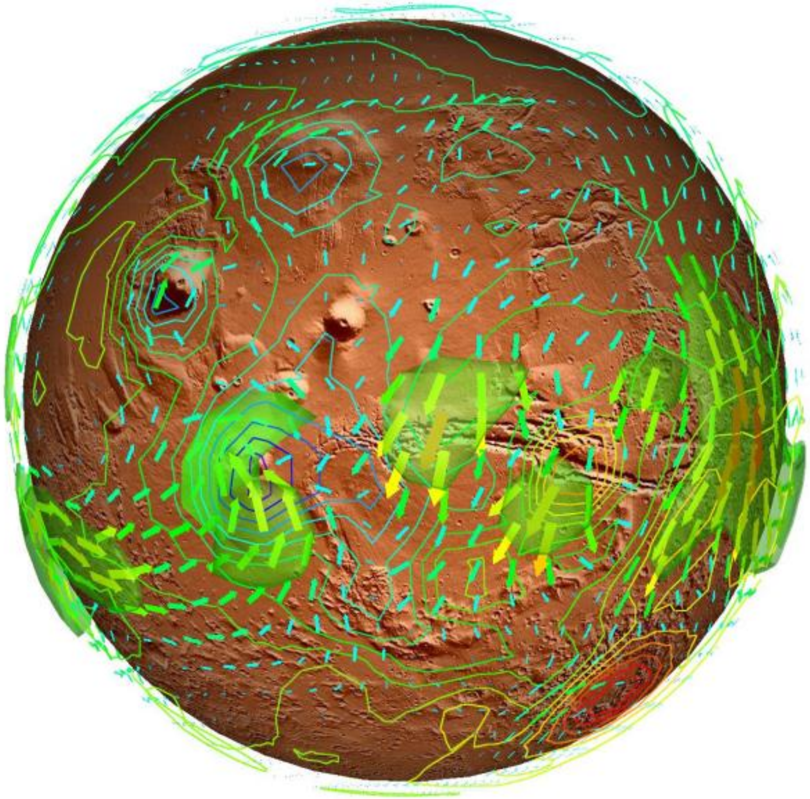
Current model

Applications

- Application to Mars



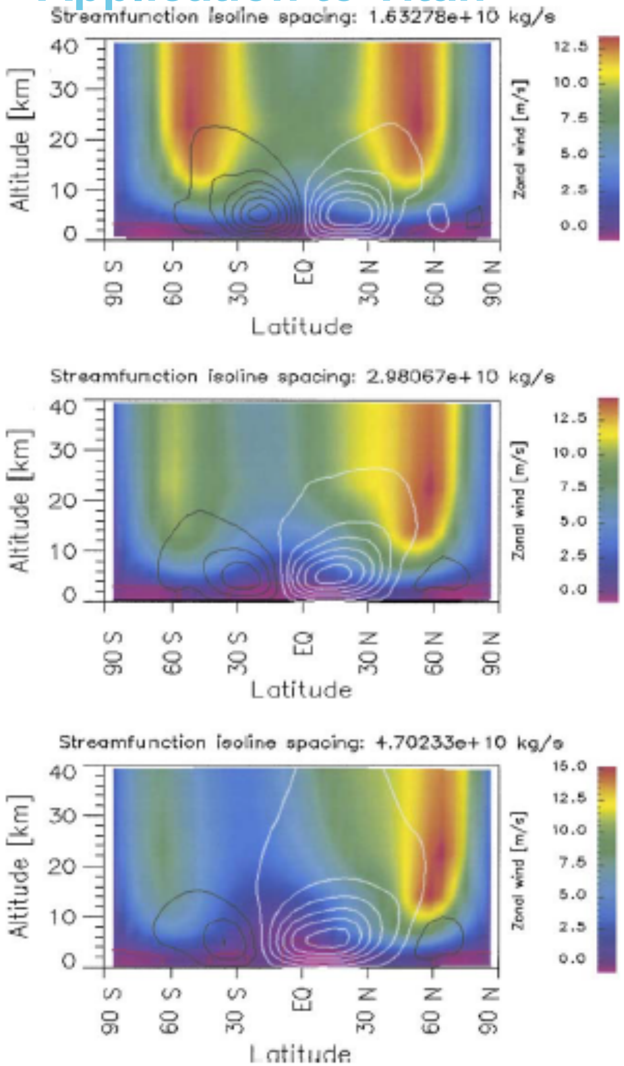
Segschneideret al (PSS, 2005)
Stenzel et al. (PSS, 2007)

- **PLASIM**
- in agreement with previous work (Hourdin et al. 1993)
- Sensitivity to obliquity
- **No dust / CO_2 cycle**
- **Fixed CO_2 concentration**

Current model

Applications

- **Application to Titan**



Grieger et al (ASR, 2004)

- **PUMA**
- in agreement with previous work (Hourdin et al. 2009)
- Newtonian forcing

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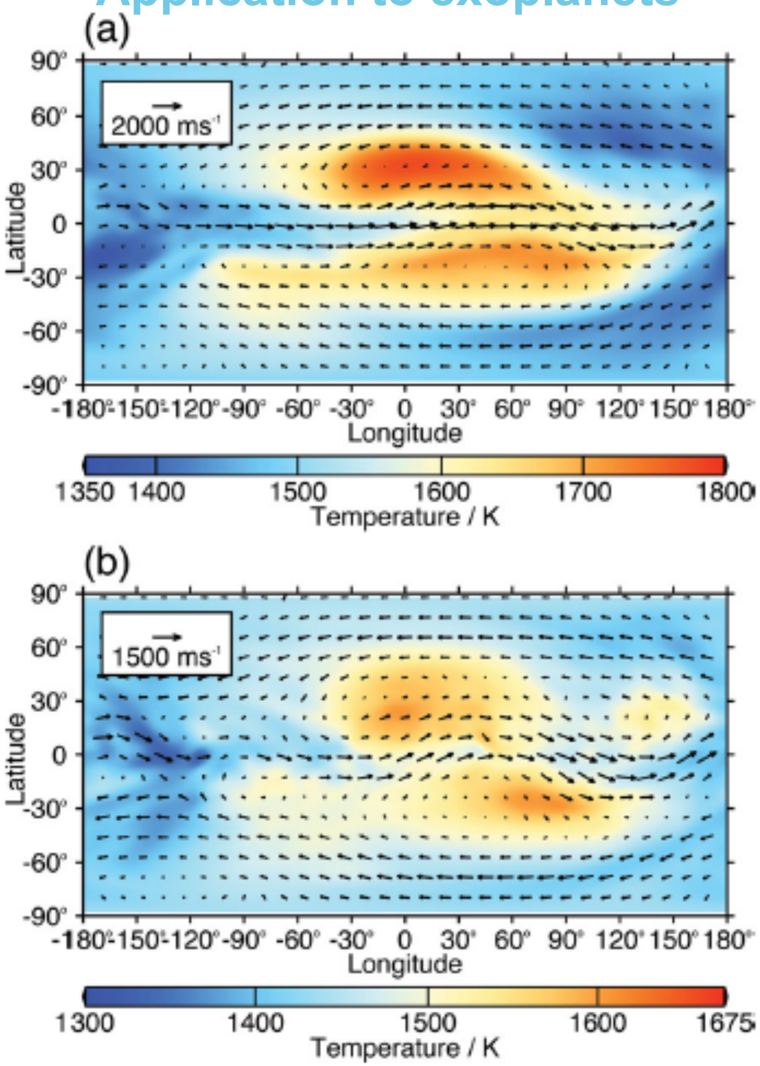
Current model

Applications

- Application to exoplanets



Gas giant planets

Bending et al. (MNRAS 2013)

- **PUMA**
- in agreement with previous work (Menou & Rauscher 2009)
- Newtonian forcing

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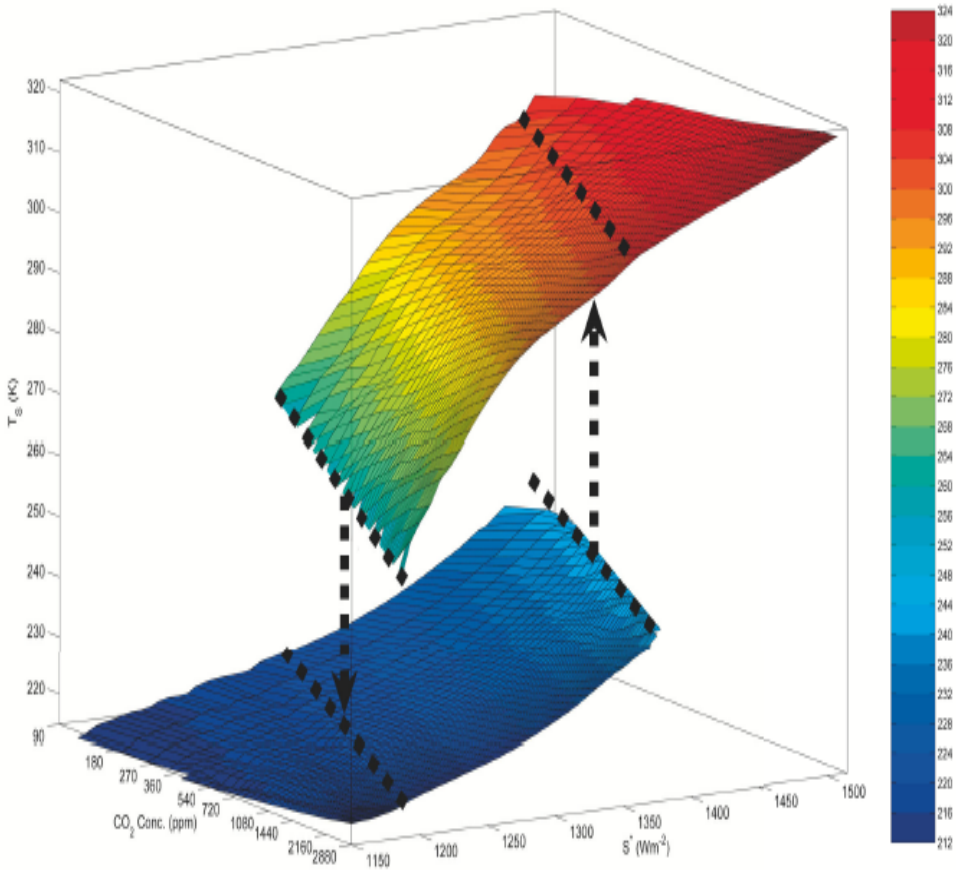
Current model

Applications

- Application to exoplanets



Earth-like planets

Lucarini et al. (Astron. Nach. 2013)

- **PLASIM**
- Sensitivity of surface temperature to heating and CO_2 concentration
- Dual band radiation scheme

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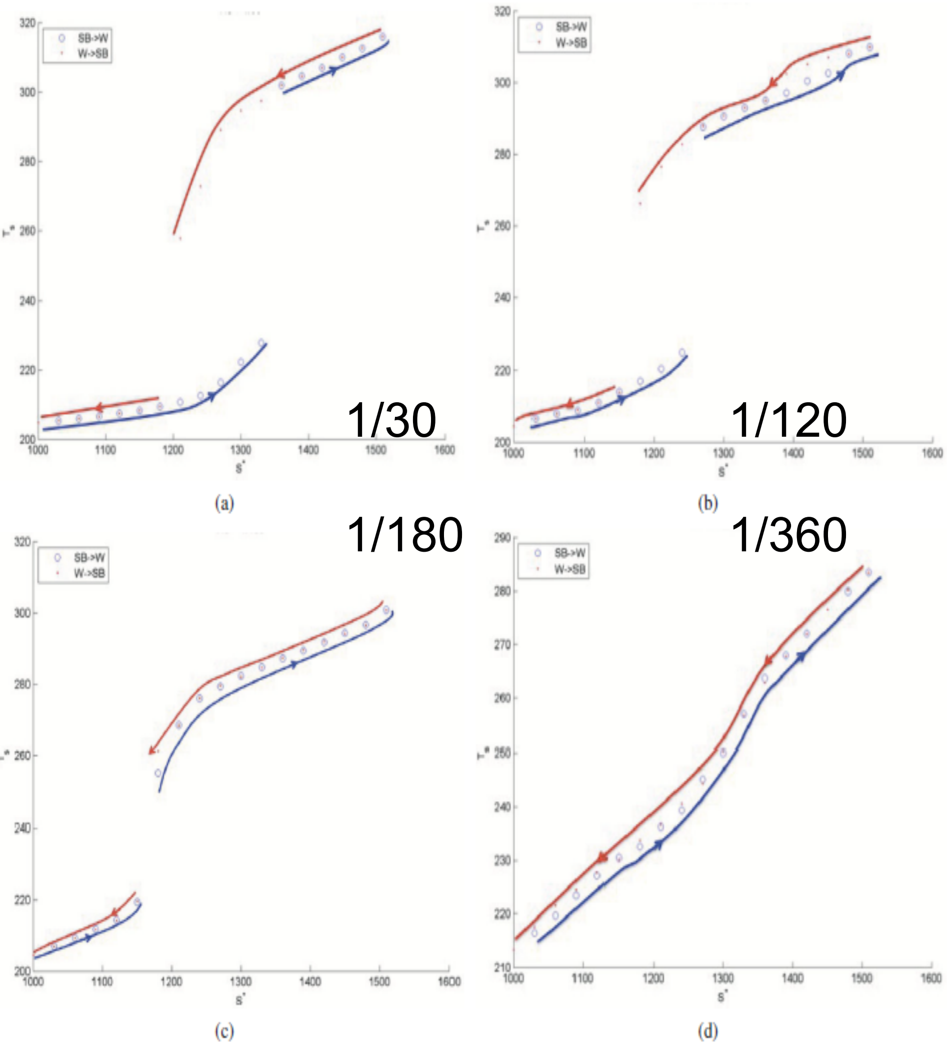
Current model

Applications

- Application to exoplanets



Earth-like planets

Lucarini et al. (Astron. Nach. 2013)

- **PLASIM**
- Sensitivity of bistability to planet rotation
- Dual band radiation scheme

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PUMA – PLASIM – SAM – SOM users

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Universite Libre de Bruxelles, Centre for Nonlinear Phenomena and Complex Systems

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Laboratoire de Physique des Oceans, Universite de Bretagne Occidentale, Brest

GERMANY

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Universität Kiel, Institut für Meereskunde
Universität Bonn, Meteorologisches Institut
Bergakademie Freiberg, Institut für Geophysik
GKSS Geesthacht, HGF, Institut für Küstenforschung
Senckenberg Forschungsinstitut und Naturmuseum, HGF, Frankfurt
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PUMA – PLASIM – SAM – SOM users cont'd

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Inst. of Atmospheric Sciences and Climate, ISAC, Italian National Research Council,Torino
European Academy Bozen/Bolzano (EURAC)
University of Genova, ISAC, Lecce
THE NETHERLANDS
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Wageningen University and Research Centre, Department of Environmental Sciences
NEW ZEALAND
National Institute of Water & Atmospheric Research, Wellington
NORWAY
Bjerknes Centre for Climate Research, Bergen
Department of Meteorology, University of Oslo,
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Institute of Numerical Mathematics, Russian Academy of Sciences, Moscow
Space Research Institute, Russian Academy of Sciences, Moscow
SINGAPORE
National University of Singapore, Centre for Remote Imaging, Sensing and Processing
SPAIN
Campus de Ourense, Sciencias, Edeficio de Fisicas, Physica de la Atmosfera y el Oceano
University of Santiago de Compostela, Faculty of Physics, Nonlinear Physics
SWEDEN
Stockholm University, Department of Meteorology
USA
University at Albany, Department of Atmospheric and Environmental Sciences
University of Colorado, Boulder, Atmospheric and Oceanic Sciences
National Oceanic Atmospheric Administration (NOAA), Earth System Res. Lab., Phys. Sci. Div., CIRES, Boulder
Princeton University, Geophysical Fluid Dynamics Laboratory
Oregon State University, College of Oceanic and Atmospheric Sciences
New York University, Courant Institute of Mathematical Sciences

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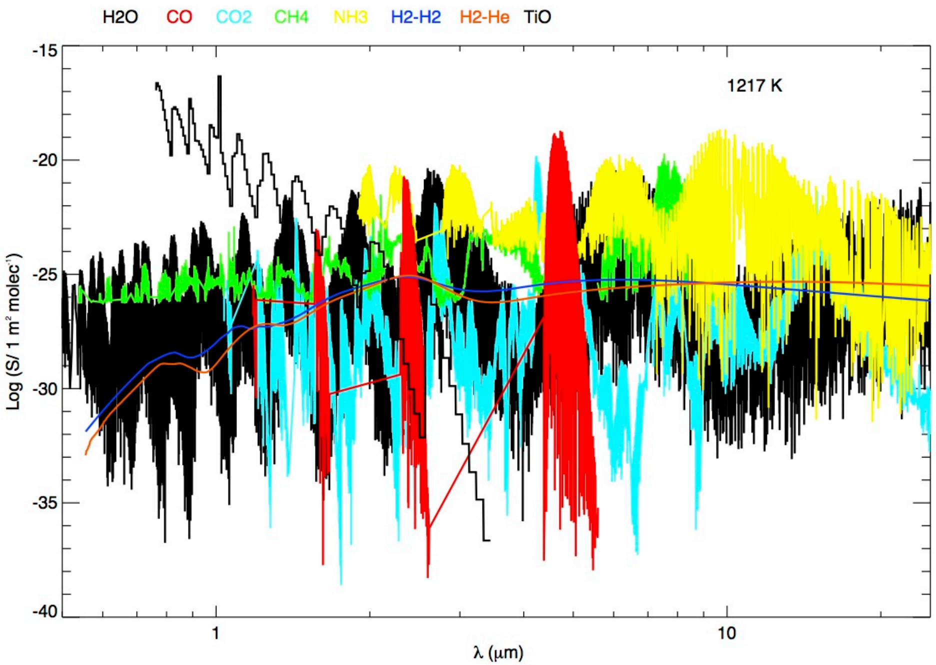
4. Future developments

- Atmospheric absorption



Line by line

- Most precise approach
- Can give you useful info

  BUT
- Several millions of lines ! (ex: 500×10^6 for hot H_2O only !) see ExoMol !!

$\Rightarrow$ Computationally expensive in CPU & disk space

- **First approximation:**

  Newtonian cooling

Principle:

- Assuming the system relaxes to its equilibrium temperature

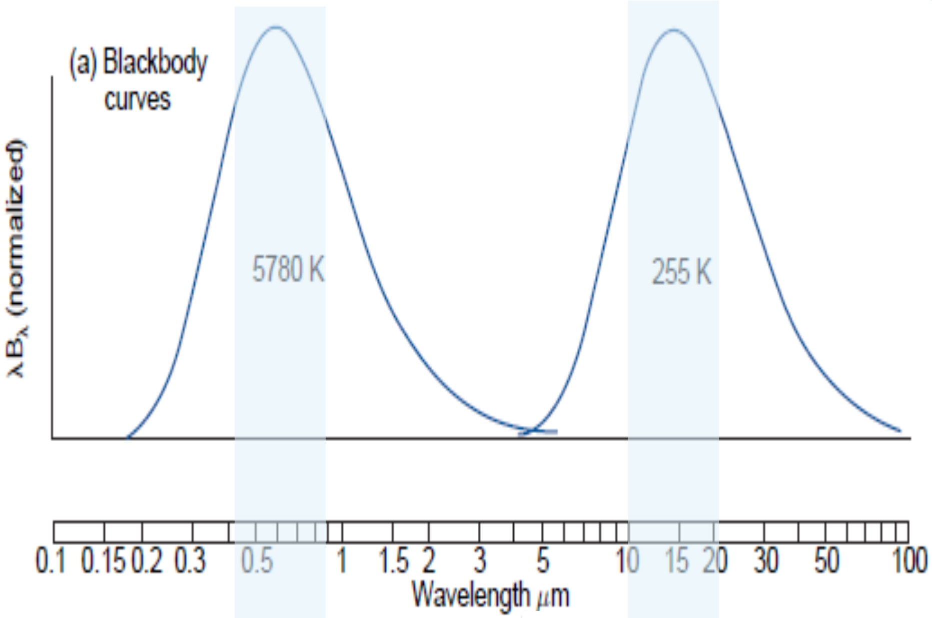
$$\dot{Q}_{\mathrm{rad}} = -\frac{1}{\tau_{\mathrm{rad}}} C_p^{(R)} (T - T_{\mathrm{eq}}),$$

$$\tau_{\mathrm{rad}} \sim \frac{\Delta p}{g} \frac{c_p}{4\sigma T^3}.$$

- Very *simple*
- **Currently in PUMA**

- 2^{nd} approximation:

  dual band radiation



Stellar heating in visible

Thermal emission in IR

Principle:

- Separation of radiation into 2 wavelength ranges
- Assumption 'grey': κ = cste

$$F_{\downarrow\mathrm{vis}}(P) = (1-A)\mu_\star F_{\mathrm{inc}} \exp\left(-\frac{1}{\mu_\star}\frac{\kappa_{\mathrm{vis}}}{g}P\right)$$

$$F_{\uparrow,\downarrow\mathrm{IR}}(P) = \int \left(1 - \exp\left[-\frac{1.66}{g}\int \kappa_{\mathrm{IR}} dP\right]\right)\frac{d\sigma T^4}{dP}dP$$

$$\kappa_{\mathrm{IR}} = \kappa_{\mathrm{IR},0}(P/P_{\mathrm{ref}})^\alpha$$

- 3 parameters: κ_{vis}, κ_{IR} and α
- Double grey: α = 0
- **Currently in PlaSim**

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RT in GCMs

k-distribution

- 3rd approximation:

  band approximation

$$T_{\bar{\nu}}(u) = \int_{\Delta\nu} e^{-k(\nu)u} \frac{d\nu}{\Delta\nu} = \int_0^{\infty} e^{-ku} h(k) dk,$$

$$g(k) = \int_0^k h(k) dk,$$

$$T_{\bar{\nu}}(u) = \int_{\Delta\nu} e^{-k(\nu)u} \frac{d\nu}{\Delta\nu} \doteq \int_0^1 e^{-k(g)u} dg,$$

Principle of *k*-distribution method:

•Replacing integrating over wavenumbers by a cumulative probability

•Probability is function easy to interpolate and calculated only once

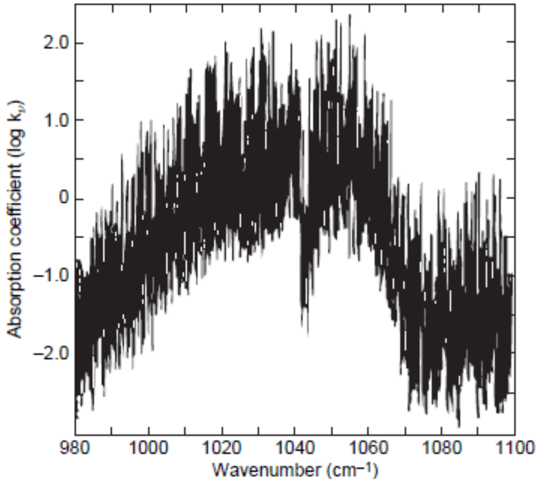
⇒ Good compromise between precision and computing “cost”

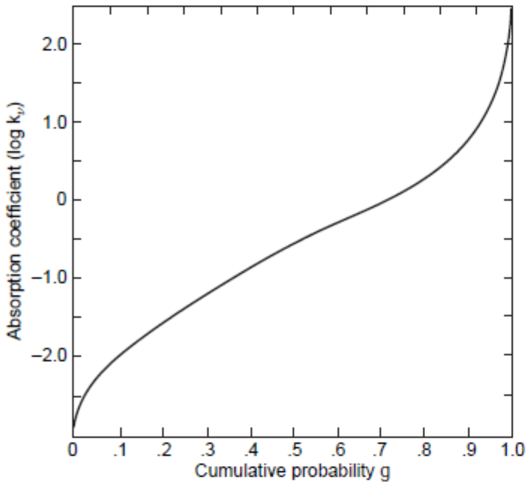
RT in GCMs

k-distribution

- 3rd approximation:

  band approximation





Principle of *k*-distribution method:

•Replacing integrating over wavenumbers by a cumulative probability

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Next generation of PlaSim

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Future developments
VIPER

- **Development of the Versatile Interactive Planet simulator for Extrasolar Research (VIPER)**

  - Being able to model circulation of Earth-like to Giant planet's atmospheres: **ANY PLANET**

  - Modular: switching on/off physical processes

  - 1 new module: RT

  - Remove assumption/restriction for Earth, extend range of parameters (e.g. rotation rate, possibility of eccentric orbit, ...)

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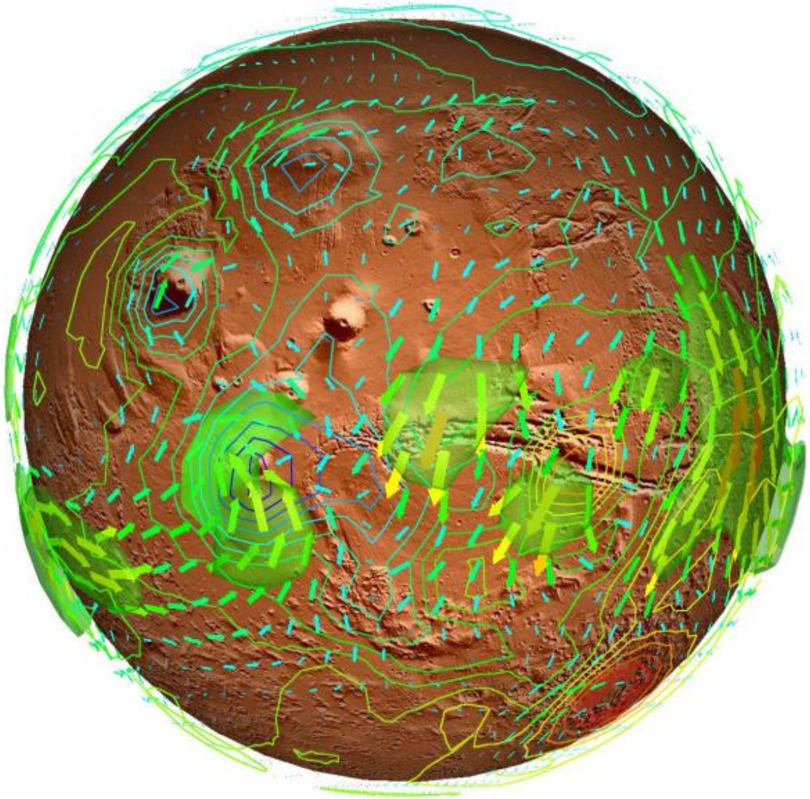
Future developments

VIPER

- **First project: Mars**



Mars

- RT
- Orography
- CO_2 cycle
- Dust
  - Radiative effect
  - Creation and transport

- Collab. J Martin-Torres (CAB, Madridf)

Future developments

VIPER

- Other possible directions

Modularity makes it easy to add/ remove complexity

A module for chemistry ?

A module for cloud ?

- Calculate or prescribe a size distribution
- Incorporate the radiative effect

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Thank you !

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Max-Planck-Institut für Meteorologie

Helmholtz-Zentrum Geesthacht
Zentrum für Material- und Küstenforschung

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