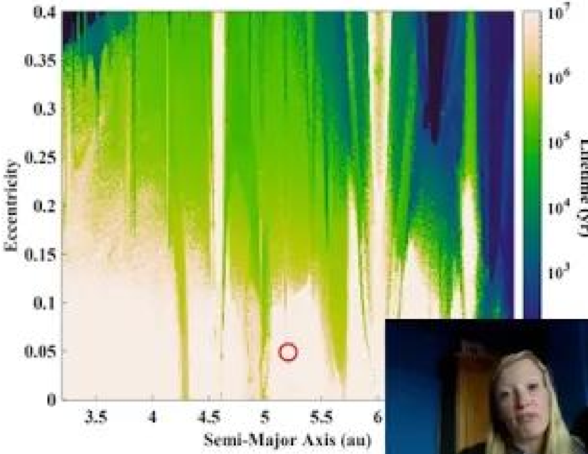
Pam Vervoort
AbGradCon 2021

How sensitive is Earth's orbit to the presence of a giant planet like Jupiter?

Methodology

- 159,201 *n*-body simulations.
- Jupiter position: 3.2 to 7.2 au
- Jupiter eccentricity: 0.0 to 0.4
- Maximum integration time of 10 Myr

- 41,652 simulations stable for 10 Myr



1
00:00:03,669 --> 00:00:02,629
jupiter is the most massive planet in

2
00:00:05,430 --> 00:00:03,679
our solar system

3
00:00:07,190 --> 00:00:05,440
and due to its proximity to the

4
00:00:09,110 --> 00:00:07,200
terrestrial planets it accepts a

5
00:00:10,629 --> 00:00:09,120
relatively large gravitational force on

6
00:00:12,549 --> 00:00:10,639
these inner planets

7
00:00:14,950 --> 00:00:12,559
jupiter essentially pushes and pulls

8
00:00:16,470 --> 00:00:14,960
them out of their ideal circular orbits

9
00:00:18,150 --> 00:00:16,480
and in this study we explore the

10
00:00:19,670 --> 00:00:18,160
influence of jupiter on the orbital

11
00:00:21,910 --> 00:00:19,680
dynamics of the earth

12
00:00:25,910 --> 00:00:21,920
and the implications for our planets

13
00:00:27,349 --> 00:00:25,920

spin dynamics and climate variability

14
00:00:29,509 --> 00:00:27,359
this is directly relevant to

15
00:00:30,470 --> 00:00:29,519
exoplanetary science as we discover more

16
00:00:32,310 --> 00:00:30,480
and more planets

17
00:00:34,470 --> 00:00:32,320
in multiplanetary systems with

18
00:00:36,470 --> 00:00:34,480
potentially habitable planets

19
00:00:38,470 --> 00:00:36,480
there has been a long lasting debate on

20
00:00:40,069 --> 00:00:38,480
whether it is beneficial for a planet in

21
00:00:41,110 --> 00:00:40,079
the habitable zone to have a giant's

22
00:00:43,110 --> 00:00:41,120
companion or not

23
00:00:45,110 --> 00:00:43,120
in terms of making that planet more or

24
00:00:48,150 --> 00:00:45,120
less a habitable

25
00:00:49,670 --> 00:00:48,160
for instance in the 1980s it was

26
00:00:51,830 --> 00:00:49,680
proposed that

27
00:00:53,990 --> 00:00:51,840
a giant planet could act as a shield and

28
00:00:55,110 --> 00:00:54,000
protect inner planets from harmful

29
00:00:57,430 --> 00:00:55,120
impacts

30
00:00:59,029 --> 00:00:57,440
but later on dynamic simulation showed

31
00:01:01,110 --> 00:00:59,039
that the impact rate could actually

32
00:01:03,270 --> 00:01:01,120
increase because jupiter jupiter

33
00:01:04,149 --> 00:01:03,280
destabilizes smaller objects out of

34
00:01:05,670 --> 00:01:04,159
their orbit

35
00:01:07,190 --> 00:01:05,680
and could actually shoot them towards

36
00:01:08,789 --> 00:01:07,200
the earth

37
00:01:10,789 --> 00:01:08,799
additionally impacts are not always

38
00:01:12,070 --> 00:01:10,799

harmful but can also carry essential

39
00:01:14,630 --> 00:01:12,080
volatiles to terrestrial

40
00:01:15,910 --> 00:01:14,640
planets that are necessary for habitable

41
00:01:19,109 --> 00:01:15,920
conditions

42
00:01:20,230 --> 00:01:19,119
so as we weighty advantages against the

43
00:01:22,310 --> 00:01:20,240
disadvantages

44
00:01:24,310 --> 00:01:22,320
of having a giant companion we should

45
00:01:26,230 --> 00:01:24,320
really consider also another important

46
00:01:27,030 --> 00:01:26,240
implications of the presence of a giant

47
00:01:31,590 --> 00:01:27,040
planet

48
00:01:33,109 --> 00:01:31,600
gravitational impact on the smaller

49
00:01:33,830 --> 00:01:33,119
planets and how it can alter their

50
00:01:37,670 --> 00:01:33,840
orbits and

51
00:01:39,429 --> 00:01:37,680
indirectly also their spin dynamics

52
00:01:41,429 --> 00:01:39,439
so currently for the earth jupiter

53
00:01:43,429 --> 00:01:41,439
drives quasi-periodic cycles in the

54
00:01:44,469 --> 00:01:43,439
elapticity or the eccentricity of the

55
00:01:47,749 --> 00:01:44,479
earth

56
00:01:50,310 --> 00:01:47,759
100

57
00:01:52,710 --> 00:01:50,320
000 kilo years long and modulated by a

58
00:01:54,710 --> 00:01:52,720
400 kilo year cycle as can be seen in

59
00:01:56,230 --> 00:01:54,720
the bottom panel

60
00:01:58,709 --> 00:01:56,240
for the earth the orbit remains

61
00:02:00,310 --> 00:01:58,719
relatively circular and the amplitude of

62
00:02:03,190 --> 00:02:00,320
the eccentricity cycles

63
00:02:05,030 --> 00:02:03,200

is small this means that the variability

64
00:02:07,270 --> 00:02:05,040
in the total amount of annual global

65
00:02:10,469 --> 00:02:07,280
mean insulation varies only

66
00:02:13,030 --> 00:02:10,479
slightly but yet these slight changes

67
00:02:14,869 --> 00:02:13,040
are sufficiently large to drive drastic

68
00:02:16,869 --> 00:02:14,879
changes in global climate

69
00:02:18,550 --> 00:02:16,879
for instance the glacial interglacial

70
00:02:22,869 --> 00:02:18,560
cycles of the last million years

71
00:02:24,470 --> 00:02:22,879
are paced at eccentricity cycles

72
00:02:26,390 --> 00:02:24,480
if you look closely enough you'll also

73
00:02:27,110 --> 00:02:26,400
see that earth's orbital inclination

74
00:02:28,869 --> 00:02:27,120
changes

75
00:02:30,470 --> 00:02:28,879
and this doesn't affect the amount of

76
00:02:32,150 --> 00:02:30,480
insulation that the earth receives on a

77
00:02:33,990 --> 00:02:32,160
global annual mean scale

78
00:02:35,350 --> 00:02:34,000
but it does impact the tilt of the earth

79
00:02:37,350 --> 00:02:35,360
relative to the sun

80
00:02:42,309 --> 00:02:37,360
which means that the distribution of the

81
00:02:45,990 --> 00:02:44,070
so you can imagine that if jupiter would

82
00:02:47,750 --> 00:02:46,000
have been on a slightly different orbit

83
00:02:49,350 --> 00:02:47,760
the orbital cycles of earth and

84
00:02:50,869 --> 00:02:49,360
consequently also the insulation

85
00:02:51,750 --> 00:02:50,879
patterns of our planet would be

86
00:02:54,710 --> 00:02:51,760
different

87
00:02:56,550 --> 00:02:54,720
so what does this mean in for in terms

88
00:02:57,910 --> 00:02:56,560

of the climate cycles and habitability

89
00:02:59,589 --> 00:02:57,920
on earth

90
00:03:01,910 --> 00:02:59,599
to answer these questions i use an

91
00:03:04,070 --> 00:03:01,920
ensemble of alternative solar system

92
00:03:05,750 --> 00:03:04,080
and body simulations and in these

93
00:03:08,070 --> 00:03:05,760
simulations that are ran by

94
00:03:09,750 --> 00:03:08,080
our collaborator john t horner the

95
00:03:10,309 --> 00:03:09,760
initial position of jupiter varies

96
00:03:13,830 --> 00:03:10,319
between

97
00:03:15,990 --> 00:03:13,840
3.2 au and 7.2 au

98
00:03:20,550 --> 00:03:16,000
the initial eccentricity of jupiter

99
00:03:22,390 --> 00:03:20,560
varies systematically between 0 and 0.4

100
00:03:23,910 --> 00:03:22,400
not all of these systems are stable some

101
00:03:25,990 --> 00:03:23,920
of them are dynamically

102
00:03:27,110 --> 00:03:26,000
unstable for instance when a planet

103
00:03:29,270 --> 00:03:27,120
collides with the sun

104
00:03:31,589 --> 00:03:29,280
with another planet or is ejected out of

105
00:03:33,350 --> 00:03:31,599
the system completely

106
00:03:35,750 --> 00:03:33,360
so the lifetime of each of those

107
00:03:37,350 --> 00:03:35,760
individual simulations are indicated in

108
00:03:40,070 --> 00:03:37,360
the figure

109
00:03:40,710 --> 00:03:40,080
the eccentricity of jupiter is indicated

110
00:03:43,350 --> 00:03:40,720
by the

111
00:03:46,869 --> 00:03:43,360
y-axis whereas the semi-major axis of

112
00:03:49,190 --> 00:03:46,879
jupiter is indicated by the x-axis

113
00:03:50,630 --> 00:03:49,200

overall simulations where jupiter has a

114
00:03:52,710 --> 00:03:50,640
low eccentricity

115
00:03:54,070 --> 00:03:52,720
they are dynamically more stable than

116
00:03:56,869 --> 00:03:54,080
when jupiter would have had a high

117
00:03:59,030 --> 00:03:56,879
eccentricity

118
00:04:01,429 --> 00:03:59,040
the red circle indicated here indicates

119
00:04:03,270 --> 00:04:01,439
our current solar system configuration

120
00:04:04,789 --> 00:04:03,280
and will be indicated in the next few

121
00:04:06,869 --> 00:04:04,799
figures as well that have the same

122
00:04:08,229 --> 00:04:06,879
outline

123
00:04:10,630 --> 00:04:08,239
so let's take a look at some of the

124
00:04:11,750 --> 00:04:10,640
results um in these figures the black

125
00:04:14,949 --> 00:04:11,760
regions indicate

126
00:04:17,990 --> 00:04:14,959
unstable simulations some of these

127
00:04:21,349 --> 00:04:18,000
regions for instance around 4.5 au

128
00:04:21,990 --> 00:04:21,359
and 6 au these are regions where saturn

129
00:04:24,150 --> 00:04:22,000
and jupiter

130
00:04:27,350 --> 00:04:24,160
are in resonance which allows for a much

131
00:04:29,189 --> 00:04:27,360
wider range of stable configurations

132
00:04:31,350 --> 00:04:29,199
there are also regions of instability

133
00:04:34,230 --> 00:04:31,360
for instance if jupiter would have been

134
00:04:36,310 --> 00:04:34,240
slightly more inward at 5 a.u

135
00:04:39,270 --> 00:04:36,320
the solar system would have been become

136
00:04:42,790 --> 00:04:39,280
dynamically unstable

137
00:04:45,189 --> 00:04:42,800
in this figure on the left we are now

138
00:04:47,110 --> 00:04:45,199

showing the maximum eccentricity that

139
00:04:49,030 --> 00:04:47,120
earth's orbit reaches

140
00:04:50,550 --> 00:04:49,040
uh for all the stable dynamical

141
00:04:52,870 --> 00:04:50,560
simulations

142
00:04:54,950 --> 00:04:52,880
in general the pattern that emerges is

143
00:04:56,230 --> 00:04:54,960
that when jupiter's eccentricity

144
00:05:01,830 --> 00:04:56,240
increases

145
00:05:03,430 --> 00:05:01,840
secondly when jupiter would be

146
00:05:05,990 --> 00:05:03,440
positioned more closely

147
00:05:08,390 --> 00:05:06,000
inwards and the rate at which earth's

148
00:05:10,629 --> 00:05:08,400
eccentricity changes

149
00:05:11,749 --> 00:05:10,639
would change as well so as jupiter would

150
00:05:14,390 --> 00:05:11,759
have been moving

151
00:05:16,390 --> 00:05:14,400
closer inwards the orbital cycles have a

152
00:05:17,909 --> 00:05:16,400
shorter duration

153
00:05:20,230 --> 00:05:17,919
currently earth's decentralized has a

154
00:05:22,870 --> 00:05:20,240
period of around 100 kilo years

155
00:05:24,390 --> 00:05:22,880
with jupiter at 3.2 au the main period

156
00:05:28,230 --> 00:05:24,400
would decrease up to

157
00:05:31,430 --> 00:05:29,909
since the annual global mean amount of

158
00:05:33,510 --> 00:05:31,440
insulation that the earth receives is

159
00:05:35,350 --> 00:05:33,520
directly a function of eccentricity

160
00:05:37,189 --> 00:05:35,360
we can calculate the maximum change in

161
00:05:38,310 --> 00:05:37,199
insulation so for a modern earth

162
00:05:41,270 --> 00:05:38,320
insulation varies

163
00:05:42,150 --> 00:05:41,280

but by roughly 0.5 watts per square

164
00:05:43,909 --> 00:05:42,160
meter

165
00:05:45,990 --> 00:05:43,919
between an eccentricity maxima and

166
00:05:47,990 --> 00:05:46,000
minimum and this has been

167
00:05:49,909 --> 00:05:48,000
driving great climatic fluctuations like

168
00:05:52,070 --> 00:05:49,919
the glacial interglacial cycles

169
00:05:53,189 --> 00:05:52,080
so in some of our simulations that we

170
00:05:55,270 --> 00:05:53,199
record here

171
00:05:57,270 --> 00:05:55,280
the difference in insulation can

172
00:05:58,790 --> 00:05:57,280
sometimes reach two or sometimes even

173
00:06:00,230 --> 00:05:58,800
five watts per square meter

174
00:06:01,909 --> 00:06:00,240
so you can imagine this could have

175
00:06:03,590 --> 00:06:01,919
massive implications for

176
00:06:05,670 --> 00:06:03,600
the climate variability on the earth's

177
00:06:07,590 --> 00:06:05,680
surface

178
00:06:09,189 --> 00:06:07,600
we can do exactly the same analysis for

179
00:06:12,230 --> 00:06:09,199
the orbital inclination

180
00:06:15,110 --> 00:06:12,240
and we find that if we change

181
00:06:16,870 --> 00:06:15,120
jupiter's orbit it doesn't majorly

182
00:06:19,189 --> 00:06:16,880
influence the maximum

183
00:06:20,230 --> 00:06:19,199
change in the orbital inclination

184
00:06:23,909 --> 00:06:20,240
however

185
00:06:26,469 --> 00:06:23,919
if we change jupiter's semi-major axis

186
00:06:27,430 --> 00:06:26,479
and move jupiter closer inwards it does

187
00:06:29,430 --> 00:06:27,440
impact

188
00:06:30,950 --> 00:06:29,440

the rate of change at which the

189
00:06:33,189 --> 00:06:30,960
inclination is changing

190
00:06:37,270 --> 00:06:33,199
so jupiter closer inward results in more

191
00:06:38,870 --> 00:06:37,280
rapid cycles in the orbital inclination

192
00:06:40,950 --> 00:06:38,880
and in terms of habitability we would

193
00:06:41,670 --> 00:06:40,960
like to investigate whether more rapid

194
00:06:44,309 --> 00:06:41,680
cycles

195
00:06:46,390 --> 00:06:44,319
or would improve the inhabitable

196
00:06:48,469 --> 00:06:46,400
habitable conditions or not

197
00:06:49,589 --> 00:06:48,479
but the orbital parameters are only part

198
00:06:51,830 --> 00:06:49,599
of the story

199
00:06:53,110 --> 00:06:51,840
and the spin motions of a planet play an

200
00:06:55,670 --> 00:06:53,120
important role for the climate

201
00:06:57,670 --> 00:06:55,680
modulation and are directly affected by

202
00:06:59,510 --> 00:06:57,680
changes in eccentricity and orbital

203
00:07:01,909 --> 00:06:59,520
inclination

204
00:07:04,230 --> 00:07:01,919
because the earth is not a rigid body it

205
00:07:06,309 --> 00:07:04,240
produces an equatorial bulge as a result

206
00:07:08,070 --> 00:07:06,319
of its really fast rotation

207
00:07:10,150 --> 00:07:08,080
and because the moon and the sun are not

208
00:07:11,990 --> 00:07:10,160
exactly aligned with the earth's equator

209
00:07:13,909 --> 00:07:12,000
where the bulge is forming they

210
00:07:15,990 --> 00:07:13,919
essentially try to pull the bulge

211
00:07:18,710 --> 00:07:16,000
towards the ecliptic which drives a

212
00:07:20,629 --> 00:07:18,720
processional motion of the earth's axis

213
00:07:23,589 --> 00:07:20,639

the orbital inclination has a direct

214
00:07:26,950 --> 00:07:23,599
influence on the earth's actual tilt

215
00:07:29,029 --> 00:07:26,960
or the oblique so what i do is i apply

216
00:07:30,950 --> 00:07:29,039
an obliquity model to the output of the

217
00:07:33,749 --> 00:07:30,960
ant body simulations to calculate how

218
00:07:35,749 --> 00:07:33,759
oblique and precession change over time

219
00:07:37,029 --> 00:07:35,759
um here i'm showing the output of the

220
00:07:39,749 --> 00:07:37,039
obliquity model for

221
00:07:40,950 --> 00:07:39,759
precession on the left and for obliquity

222
00:07:44,950 --> 00:07:40,960
on the right

223
00:07:47,029 --> 00:07:44,960
um and i'm using um them on

224
00:07:48,070 --> 00:07:47,039
previous simulations that are most

225
00:07:50,629 --> 00:07:48,080
similar uh

226
00:07:52,230 --> 00:07:50,639
to earth's current earth so in blue i

227
00:07:53,990 --> 00:07:52,240
plot the historical values for

228
00:07:55,830 --> 00:07:54,000
precession and obliquity

229
00:07:57,270 --> 00:07:55,840
and in orange are the values that we

230
00:07:57,990 --> 00:07:57,280
calculate for the simulation more

231
00:08:01,670 --> 00:07:58,000
similar to

232
00:08:03,670 --> 00:08:01,680
our current solar system and you see the

233
00:08:05,270 --> 00:08:03,680
comparison between the two figures shows

234
00:08:08,309 --> 00:08:05,280
that the model is working properly and

235
00:08:10,309 --> 00:08:08,319
it validates our method

236
00:08:12,230 --> 00:08:10,319
so this obliquity model was applied to

237
00:08:13,350 --> 00:08:12,240
all the stable alternative solar system

238
00:08:16,309 --> 00:08:13,360

simulations

239
00:08:18,550 --> 00:08:16,319
for obliquity on the left it becomes

240
00:08:20,150 --> 00:08:18,560
evident that as we move jupiter closer

241
00:08:22,309 --> 00:08:20,160
inwards

242
00:08:23,510 --> 00:08:22,319
it results in much longer obliquity

243
00:08:27,029 --> 00:08:23,520
cycles

244
00:08:28,790 --> 00:08:27,039
the rate at which earth's axis precesses

245
00:08:30,469 --> 00:08:28,800
is not so much dependent on the

246
00:08:32,870 --> 00:08:30,479
semi-major axis or the

247
00:08:34,949 --> 00:08:32,880
eccentricity of jupiter but rather by

248
00:08:36,550 --> 00:08:34,959
the planetary architecture of the

249
00:08:39,990 --> 00:08:36,560
alternative solar system and the

250
00:08:41,909 --> 00:08:40,000
resonances within it

251
00:08:43,829 --> 00:08:41,919
now we find this interesting feature

252
00:08:45,910 --> 00:08:43,839
that when jupiter is closer inwards the

253
00:08:47,590 --> 00:08:45,920
eccentricity cycles that determine the

254
00:08:48,949 --> 00:08:47,600
total amount of insulation are

255
00:08:50,870 --> 00:08:48,959
relatively short

256
00:08:52,230 --> 00:08:50,880
while the obliquity cycles that control

257
00:08:54,630 --> 00:08:52,240
the distribution of the

258
00:08:56,070 --> 00:08:54,640
insulation are relatively long and this

259
00:08:57,030 --> 00:08:56,080
can have some interesting climatic

260
00:08:59,590 --> 00:08:57,040
consequences

261
00:09:01,190 --> 00:08:59,600
as various climate feedbacks act on

262
00:09:02,949 --> 00:09:01,200
different time skills

263
00:09:04,790 --> 00:09:02,959

uh for instance what would happen to the

264
00:09:05,829 --> 00:09:04,800
surface climate if the eccentricity

265
00:09:09,190 --> 00:09:05,839
cycles are

266
00:09:11,030 --> 00:09:09,200
as short as thirty 000 year

267
00:09:12,949 --> 00:09:11,040
would we just experience really rapid

268
00:09:14,550 --> 00:09:12,959
glacial interglacial cycles or would the

269
00:09:17,509 --> 00:09:14,560
rate of change be

270
00:09:19,269 --> 00:09:17,519
too high for ice caps to grow and cover

271
00:09:21,110 --> 00:09:19,279
large surfaces

272
00:09:23,110 --> 00:09:21,120
so what would happen to atmospheric

273
00:09:26,790 --> 00:09:23,120
dynamics or ocean circulations that are

274
00:09:28,470 --> 00:09:26,800
also important climate controllers

275
00:09:30,389 --> 00:09:28,480
we took a first step at trying to

276
00:09:32,790 --> 00:09:30,399
simulate the change in climate evolution

277
00:09:35,190 --> 00:09:32,800
across a one million year time interval

278
00:09:37,269 --> 00:09:35,200
and use a simple energy moisture balance

279
00:09:39,910 --> 00:09:37,279
model that is coupled to a dynamic 3d

280
00:09:41,910 --> 00:09:39,920
ocean model and a sea ice model

281
00:09:44,150 --> 00:09:41,920
while applying also time varying

282
00:09:45,670 --> 00:09:44,160
astronomical forcing so the figure shown

283
00:09:48,310 --> 00:09:45,680
here shows the simulation most

284
00:09:50,230 --> 00:09:48,320
comparable to our modern solar system

285
00:09:51,750 --> 00:09:50,240
earth's eccentricity cycles are roughly

286
00:09:54,949 --> 00:09:51,760
100 kilo years long

287
00:09:59,030 --> 00:09:54,959
and vary between zero and 0.5 obliquity

288
00:10:01,430 --> 00:09:59,040

cycles are roughly 40 kilo years long

289
00:10:02,550 --> 00:10:01,440
we find that as we simulate the sea ice

290
00:10:04,790 --> 00:10:02,560
variability

291
00:10:06,150 --> 00:10:04,800
seasonal sea ice varies with mainly

292
00:10:08,550 --> 00:10:06,160
eccentricity

293
00:10:12,150 --> 00:10:08,560
whereas the year round sea ice varies

294
00:10:16,389 --> 00:10:14,310
the figure here shows a simulation where

295
00:10:17,269 --> 00:10:16,399
the planetary architecture is very

296
00:10:19,190 --> 00:10:17,279
different

297
00:10:21,509 --> 00:10:19,200
jupiter is much closer inwards earth's

298
00:10:22,230 --> 00:10:21,519
eccentricity cycles are 30 kilo years

299
00:10:24,710 --> 00:10:22,240
long

300
00:10:26,550 --> 00:10:24,720
and very very small amplitude whereas

301
00:10:28,949 --> 00:10:26,560
the obliquity cycles are roughly

302
00:10:32,870 --> 00:10:28,959
30 000 kilo years long and very

303
00:10:35,430 --> 00:10:32,880
drastically between 20 and 30 degrees

304
00:10:36,470 --> 00:10:35,440
in this case the seasonal sea ice varies

305
00:10:38,550 --> 00:10:36,480
with the obliquity

306
00:10:40,389 --> 00:10:38,560
and the year-round sea ice is only

307
00:10:42,389 --> 00:10:40,399
present when the obliquity is low enough

308
00:10:43,509 --> 00:10:42,399
to sustain sea ice throughout the summer

309
00:10:45,350 --> 00:10:43,519
months

310
00:10:46,710 --> 00:10:45,360
the surface climate dynamics between the

311
00:10:49,509 --> 00:10:46,720
two configurations are

312
00:10:51,269 --> 00:10:49,519
just very very different and i should

313
00:10:52,949 --> 00:10:51,279

also note that the model used here is

314
00:10:54,310 --> 00:10:52,959
relatively simple and many of the

315
00:10:56,630 --> 00:10:54,320
climate feedbacks are

316
00:10:59,190 --> 00:10:56,640
not included for instance we do not

317
00:11:01,190 --> 00:10:59,200
simulate land-based eyes

318
00:11:02,470 --> 00:11:01,200
which can have very different dynamics

319
00:11:05,190 --> 00:11:02,480
to see

320
00:11:06,710 --> 00:11:05,200
sea ice also the response times is

321
00:11:08,710 --> 00:11:06,720
different than that of sea ice

322
00:11:10,389 --> 00:11:08,720
so in future work we do aim to use a

323
00:11:12,230 --> 00:11:10,399
more complex climate model that also

324
00:11:13,269 --> 00:11:12,240
uses a dynamic atmosphere so we can

325
00:11:14,949 --> 00:11:13,279
account for

326
00:11:18,069 --> 00:11:14,959
changing wind patterns and cloud

327
00:11:21,110 --> 00:11:19,590
so i will leave the conclusions up here

328
00:11:22,790 --> 00:11:21,120
but i do want to emphasize

329
00:11:24,870 --> 00:11:22,800
that as we find more planets in the

330
00:11:26,949 --> 00:11:24,880
habitable zone in multiplanetary systems

331
00:11:28,870 --> 00:11:26,959
we should not ignore the long-term

332
00:11:30,790 --> 00:11:28,880
orbital evolution as we assess a

333
00:11:32,389 --> 00:11:30,800
planet's habitability