

o oddziaływaniu chmur z aerozolem atmosferycznym

Sylwester Arabas



jak powstają chmury?

- Coulier 1875: „Note sur la nouvelle propriété de l'air”
- Aitken 1880: „On Dust, Fogs and Clouds”
- ...

WIKIPEDIA

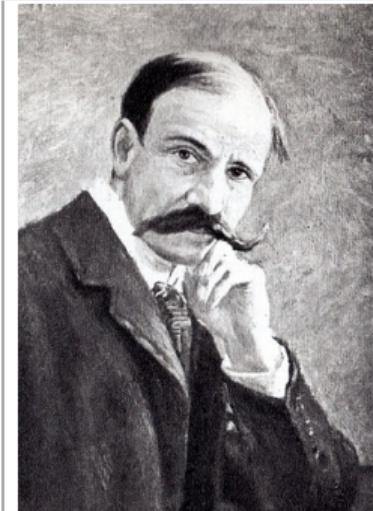
Maurycy Pius Rudzki

Maurycy Pius Rudzki (b. 1862, d. 1916) was the first person to call himself a professor of geophysics. He held the Chair of Geophysics at the Jagiellonian University in Kraków, and established the Institute of Geophysics there in 1895. His research specialty was elastic anisotropy, as applied to wave propagation in the earth, and he established many of the fundamental results in that arena. [1]

References

1. Slawinski, Michael A., WAVES AND RAYS IN ELASTIC CONTINUA, 2007: "Archived copy" (<https://archive.is/20120715001056/http://samizdat.mines.edu/wavesandrays/>). Archived from the original (<http://samizdat.mines.edu/wavesandrays/>) on 2012-07-15. Retrieved 2010-06-30.

Maurycy Pius Rudzki



„Zasady meteorologii” (1917)

<http://pbc.gda.pl/dlibra/docmetadata?id=18434>

...

„Zasady meteorologii” (1917)

<http://pbc.gda.pl/dlibra/docmetadata?id=18434>

W swobodnej atmosferze do skroplenia potrzebne są „jądra skroplenia”, dokoła których para skupia się i zamienia w wodę ...

„Zasady meteorologii” (1917)

<http://pbc.gda.pl/dlibra/docmetadata?id=18434>

W swobodnej atmosferze do skroplenia potrzebne są „jądra skroplenia”, dokoła których para skupia się i zamienia w wodę ...

Po miastach powietrze zawiera dużo dymu, molekułów kwasów i.t.d. Wszystko to są hygroskopijne ciała skupiające parę nawet wtedy, gdy powietrze nie jest jeszcze nasycone ...

„Zasady meteorologii” (1917)

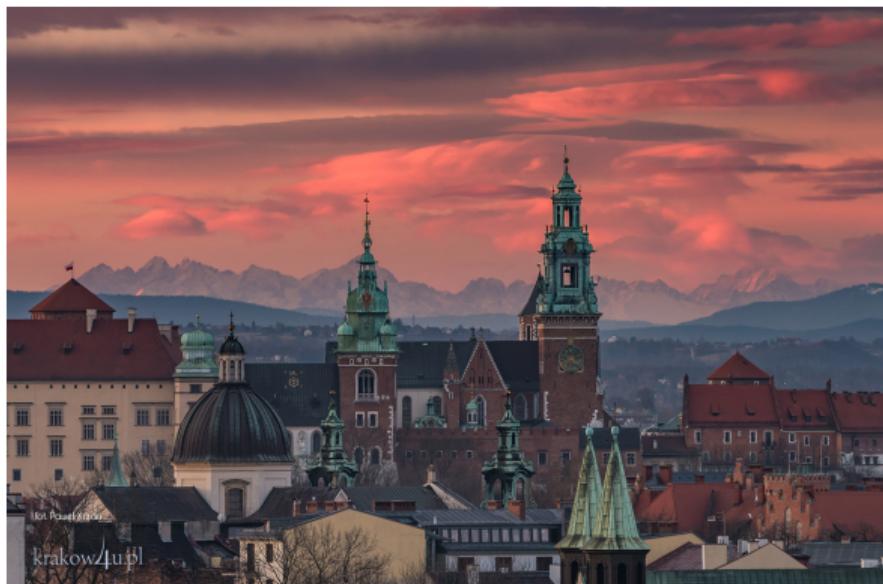
<http://pbc.gda.pl/dlibra/docmetadata?id=18434>

W swobodnej atmosferze do skroplenia potrzebne są „jądra skroplenia”, dokoła których para skupia się i zamienia w wodę ...

Po miastach powietrze zawiera dużo dymu, molekułów kwasów i.t.d. Wszystko to są hygroskopijne ciała skupiające parę nawet wtedy, gdy powietrze nie jest jeszcze nasycone ...

Wszystko, co dotychczas powiedzieliśmy, odnosi się jeno do samotnych kropel. Tymczasem, jak to słusznie zauważył M. Smoluchowski zwykle spada nie jedna kropla, ale całe mnóstwo...

„Po miastach ... hygroskopijne ciała skupiające parę ...”



copyright: Paweł Krzan / krakow4u.pl (reproduced without permission under fair usage assumption)

„Po miastach ... hygroskopijne ciała skupiające parę ...”



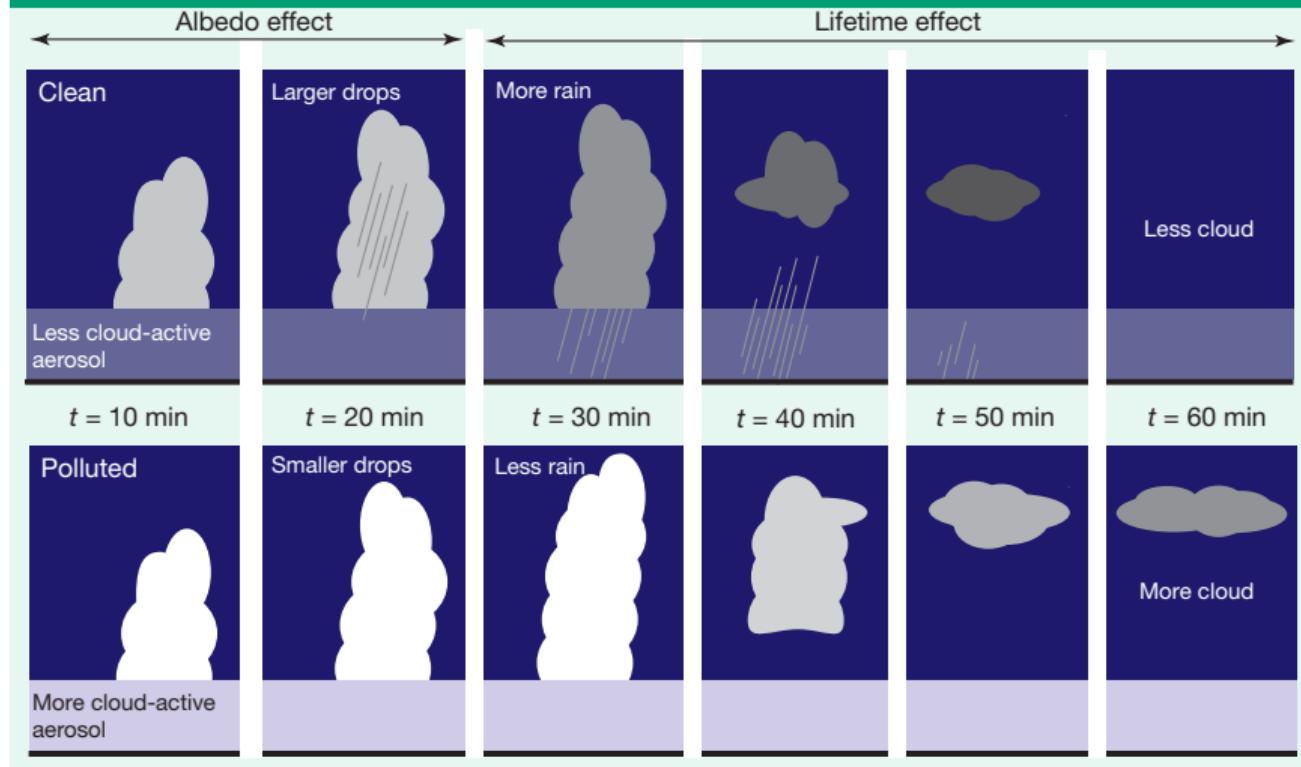
copyright: Paweł Krzan / krakow4u.pl (reproduced without permission under fair usage assumption)

no particles \rightsquigarrow no clouds

<https://www.youtube.com/watch?v=EneDwu0HrVg>

Stevens and Feingold, 2009 (Nature)

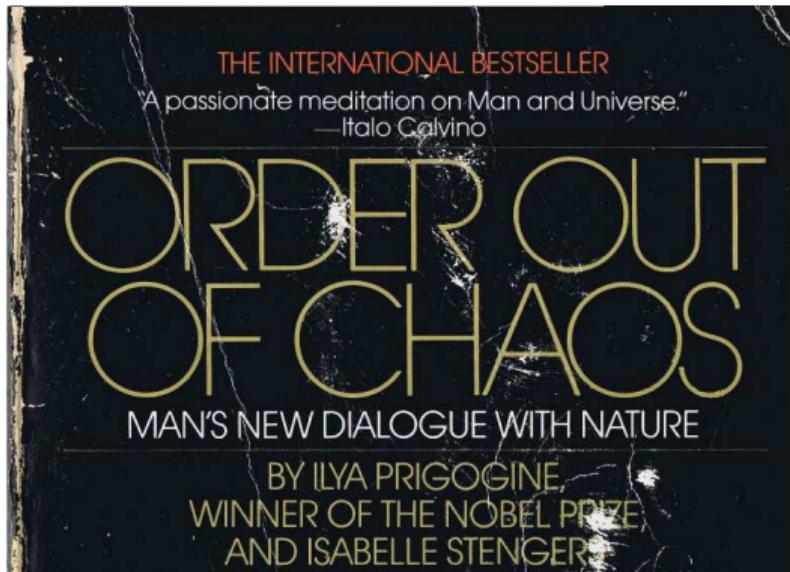
doi:10.1038/nature08281



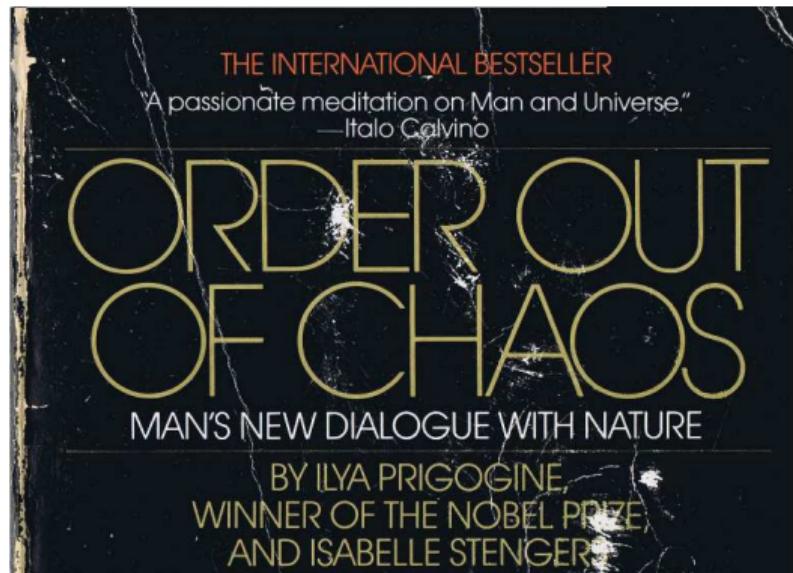
doi:10.1038/490040a

“there is something captivating about the idea that fine particulate matter, suspended almost invisibly in the atmosphere, holds the key to some of the greatest mysteries of climate science”

... micro vs. macro ...



... micro vs. macro ...

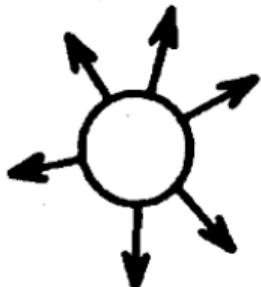


Prigogine and Stengers 1984

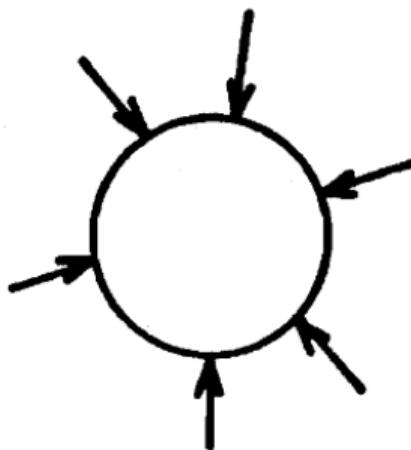
"Much of this book has centered around the relation between the microscopic and the macroscopic. One of the most important problems in evolutionary theory is the eventual feedback between macroscopic structures and microscopic events: macroscopic structures emerging from microscopic events would in turn lead to a modification of the microscopic mechanisms."

przykład bifurkacji z Prigogine & Stengers 1984

ORDER OUT OF CHAOS 188



(a)



(b)

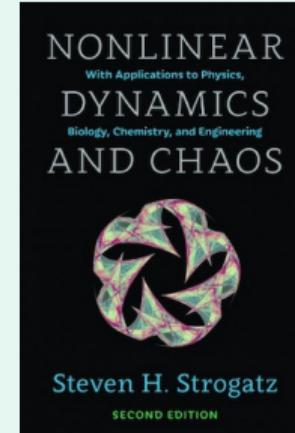
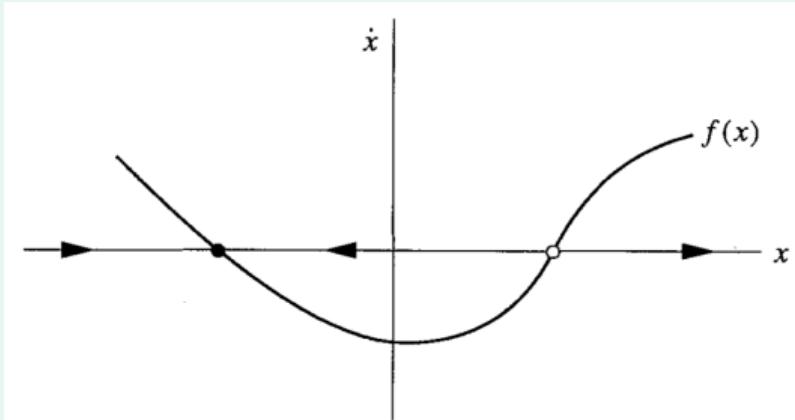
Figure 19. Nucleation of a liquid droplet in a supersaturated vapor. (a) droplet smaller than the critical size; (b) droplet larger than the critical size. The existence of the threshold has been experimentally verified for dissipative structures.

krótki kurs analizy bifurkacji (1/2)

Strogatz 2014 (sect. 2.2): fixed points and stability

graphical (qualitative) analysis
of a non-linear one-dimensional dynamical system:

$$\dot{x} = f(x)$$



krótki kurs analizy bifurkacji (2/2)

Strogatz 2014 (sect. 3.1): saddle-node bifurcation

prototypical example of saddle-node bifurcation:

$$\dot{x} = r + x^2$$

r : parameter (distinct regimes if positive, negative or zero)

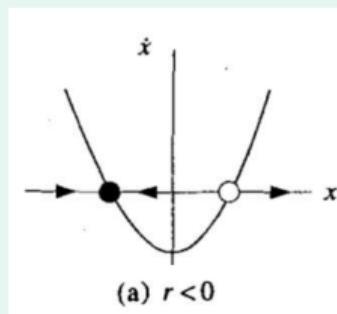
krótki kurs analizy bifurkacji (2/2)

Strogatz 2014 (sect. 3.1): saddle-node bifurcation

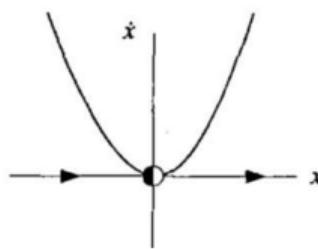
prototypical example of saddle-node bifurcation:

$$\dot{x} = r + x^2$$

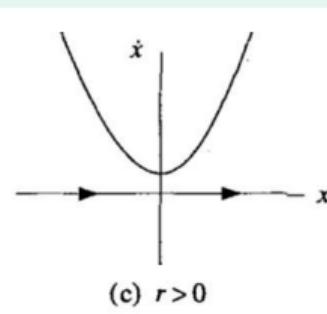
r : parameter (distinct regimes if positive, negative or zero)



(a) $r < 0$



(b) $r = 0$



(c) $r > 0$

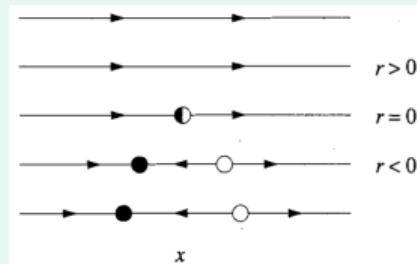
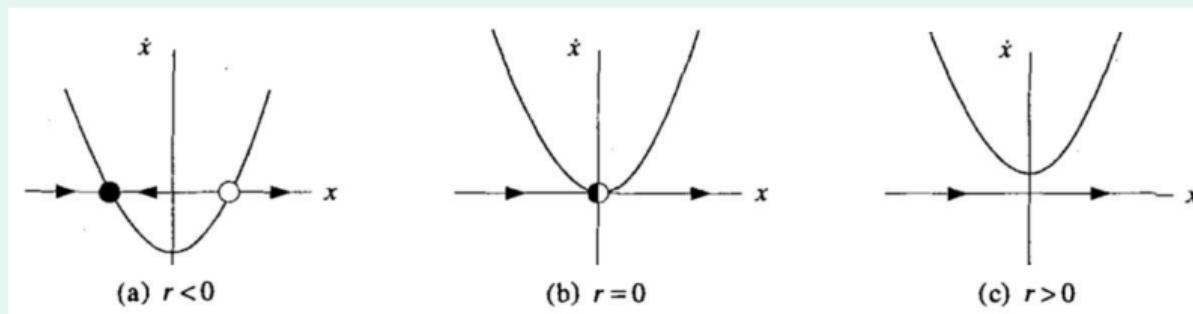
krótki kurs analizy bifurkacji (2/2)

Strogatz 2014 (sect. 3.1): saddle-node bifurcation

prototypical example of saddle-node bifurcation:

$$\dot{x} = r + x^2$$

r: parameter (distinct regimes if positive, negative or zero)



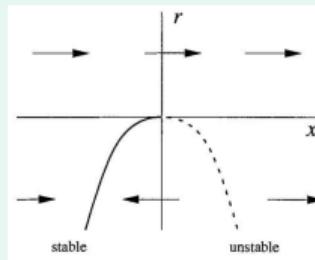
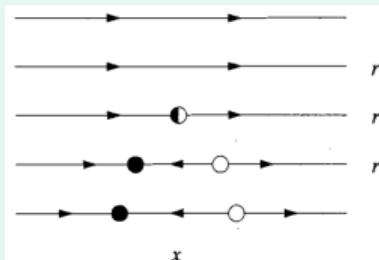
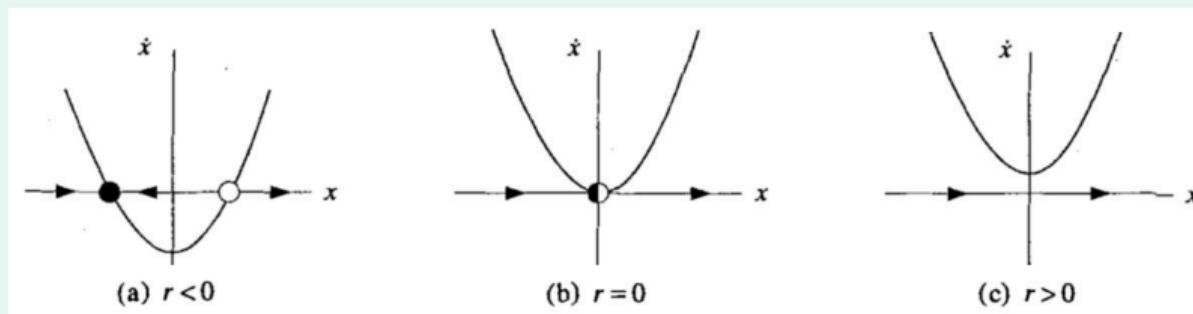
krótki kurs analizy bifurkacji (2/2)

Strogatz 2014 (sect. 3.1): saddle-node bifurcation

prototypical example of saddle-node bifurcation:

$$\dot{x} = r + x^2$$

r : parameter (distinct regimes if positive, negative or zero)



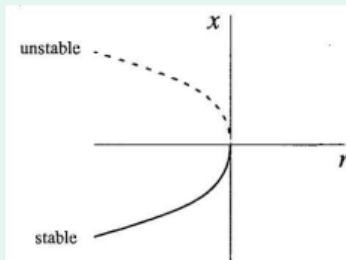
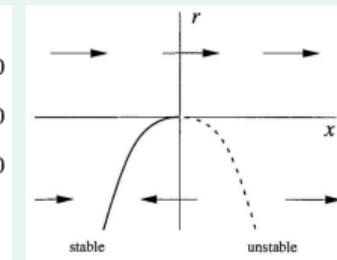
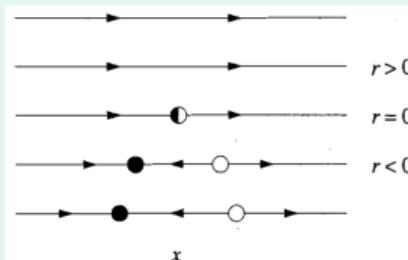
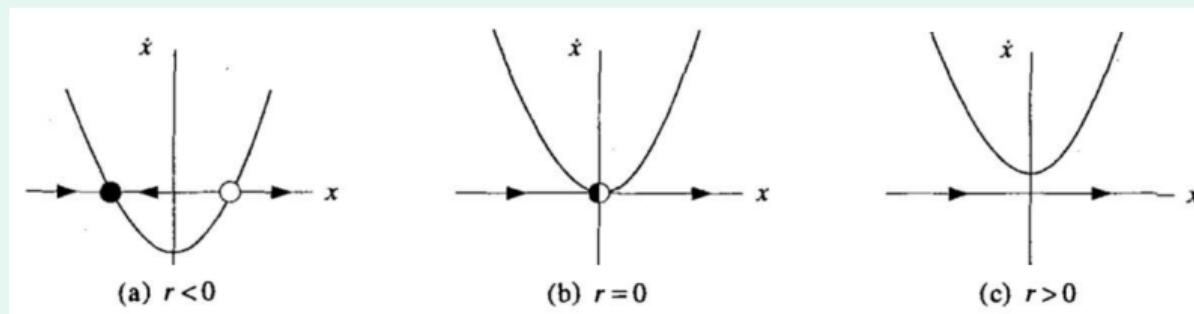
krótki kurs analizy bifurkacji (2/2)

Strogatz 2014 (sect. 3.1): saddle-node bifurcation

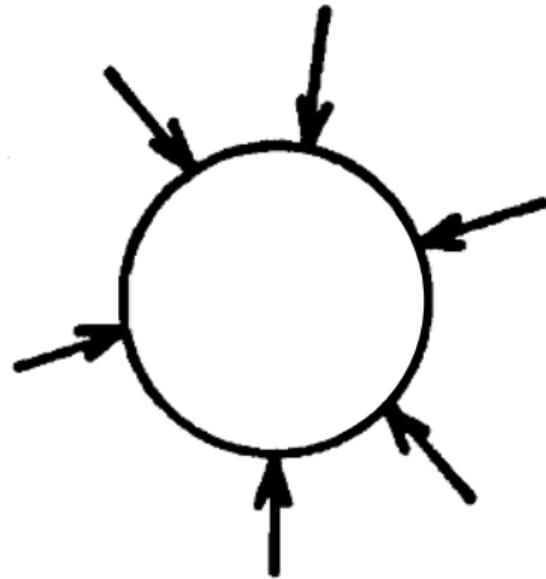
prototypical example of saddle-node bifurcation:

$$\dot{x} = r + x^2$$

r : parameter (distinct regimes if positive, negative or zero)



opis kondensacji i parowania kropli: dyfuzja masy i ciepła

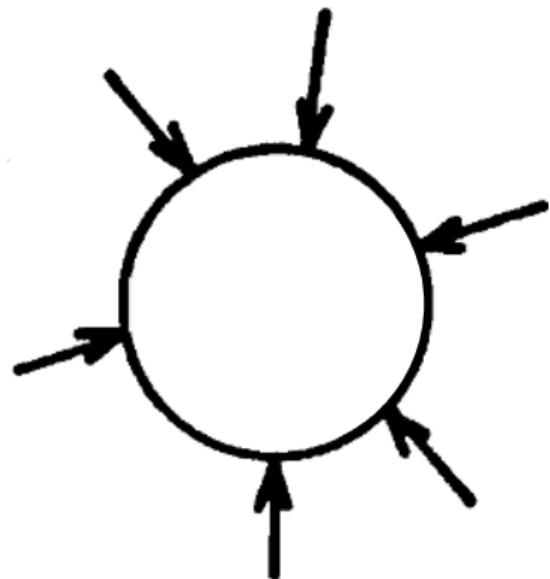


opis kondensacji i parowania kropli: dyfuzja masy i ciepła

Fick's and Fourier's laws combined

spherical geometry

$$\dot{r}_w = \frac{1}{r_w} \frac{D_{\text{eff}}}{\rho_w} (\rho_v - \rho_o)$$

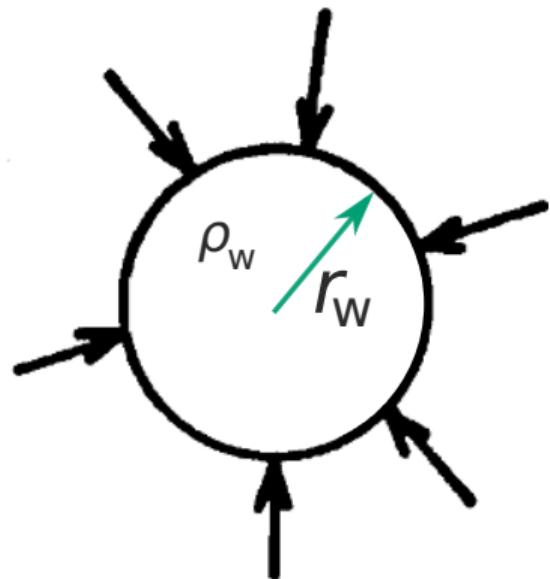


opis kondensacji i parowania kropli: dyfuzja masy i ciepła

Fick's and Fourier's laws combined

spherical geometry

$$\dot{r}_w = \frac{1}{r_w} \frac{D_{\text{eff}}}{\rho_w} (\rho_v - \rho_o)$$

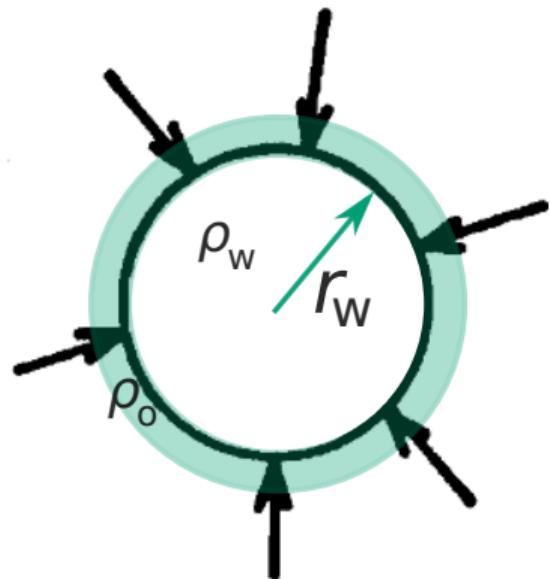


opis kondensacji i parowania kropli: dyfuzja masy i ciepła

Fick's and Fourier's laws combined

spherical geometry

$$\dot{r}_w = \frac{1}{r_w} \frac{D_{\text{eff}}}{\rho_w} (\rho_v - \rho_o)$$

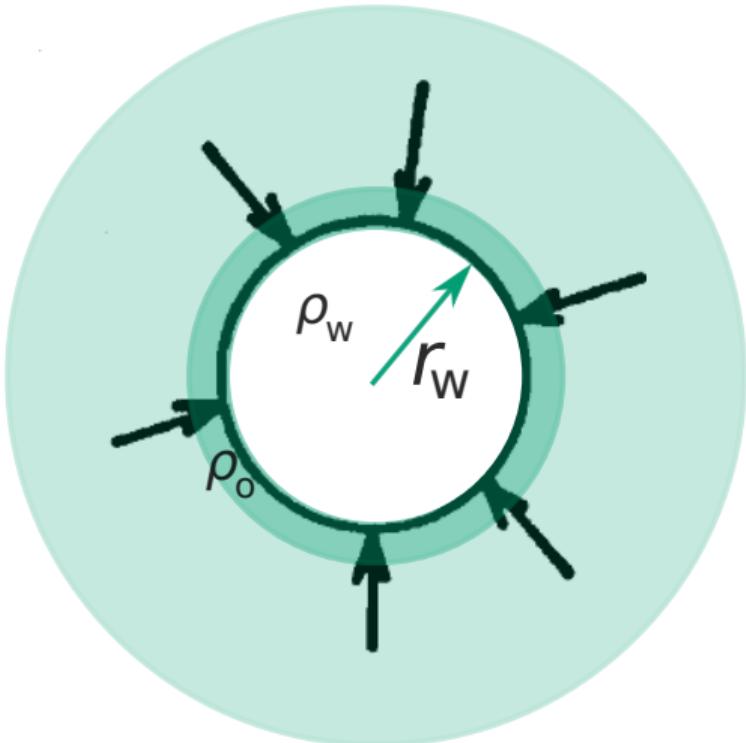


opis kondensacji i parowania kropli: dyfuzja masy i ciepła

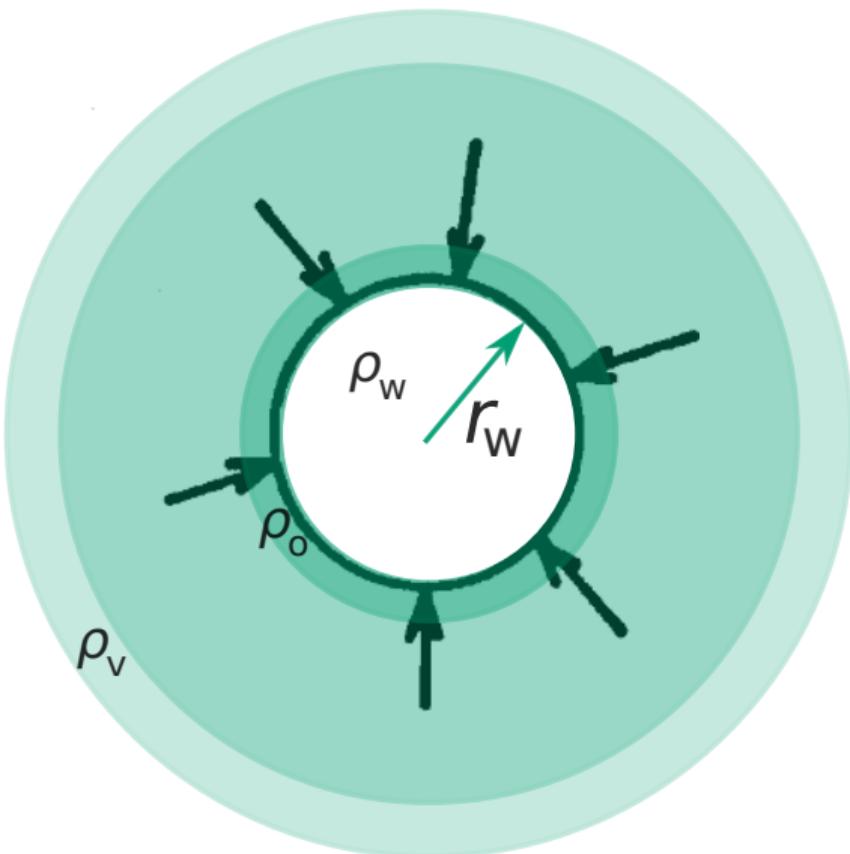
Fick's and Fourier's laws combined

spherical geometry

$$\dot{r}_w = \frac{1}{r_w} \frac{D_{\text{eff}}}{\rho_w} (\rho_v - \rho_o)$$



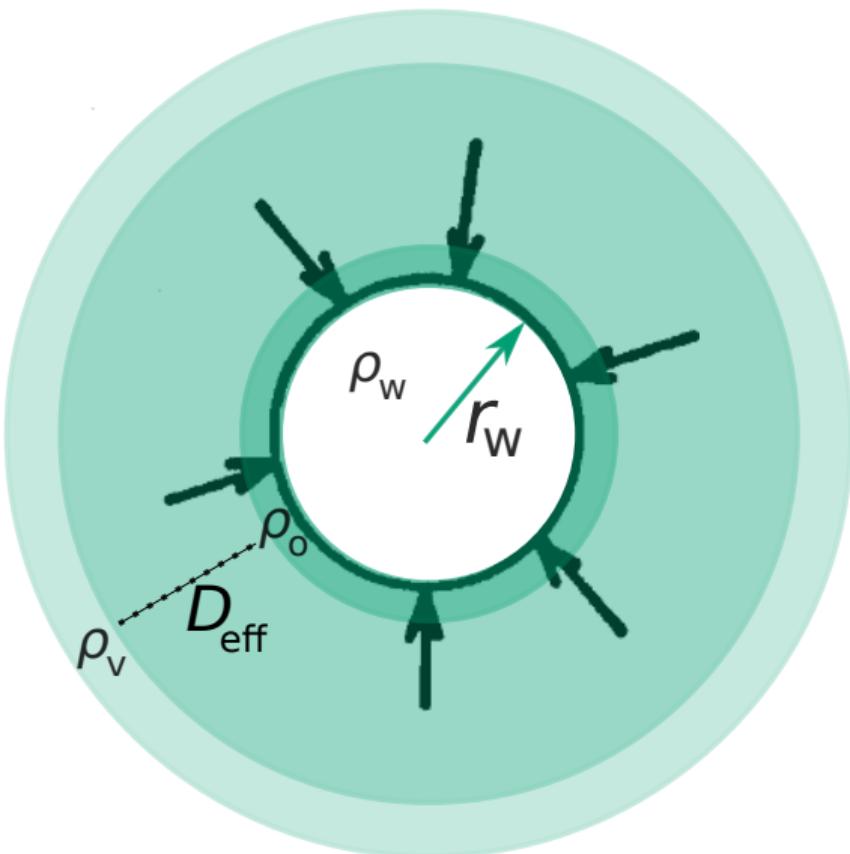
opis kondensacji i parowania kropli: dyfuzja masy i ciepła



Fick's and Fourier's laws combined
spherical geometry

$$\dot{r}_w = \frac{1}{r_w} \frac{D_{\text{eff}}}{\rho_w} (\rho_v - \rho_o)$$

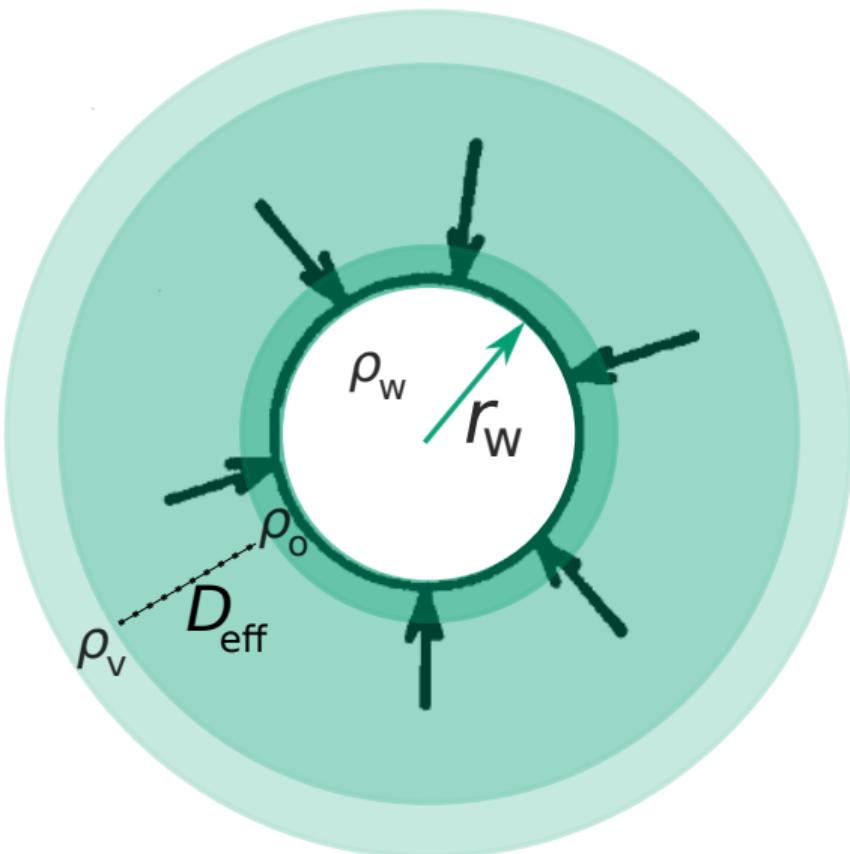
opis kondensacji i parowania kropli: dyfuzja masy i ciepła



Fick's and Fourier's laws combined
spherical geometry

$$\dot{r}_w = \frac{1}{r_w} \frac{D_{\text{eff}}}{\rho_w} (\rho_v - \rho_o)$$

opis kondensacji i parowania kropli: dyfuzja masy i ciepła



Fick's and Fourier's laws combined
spherical geometry

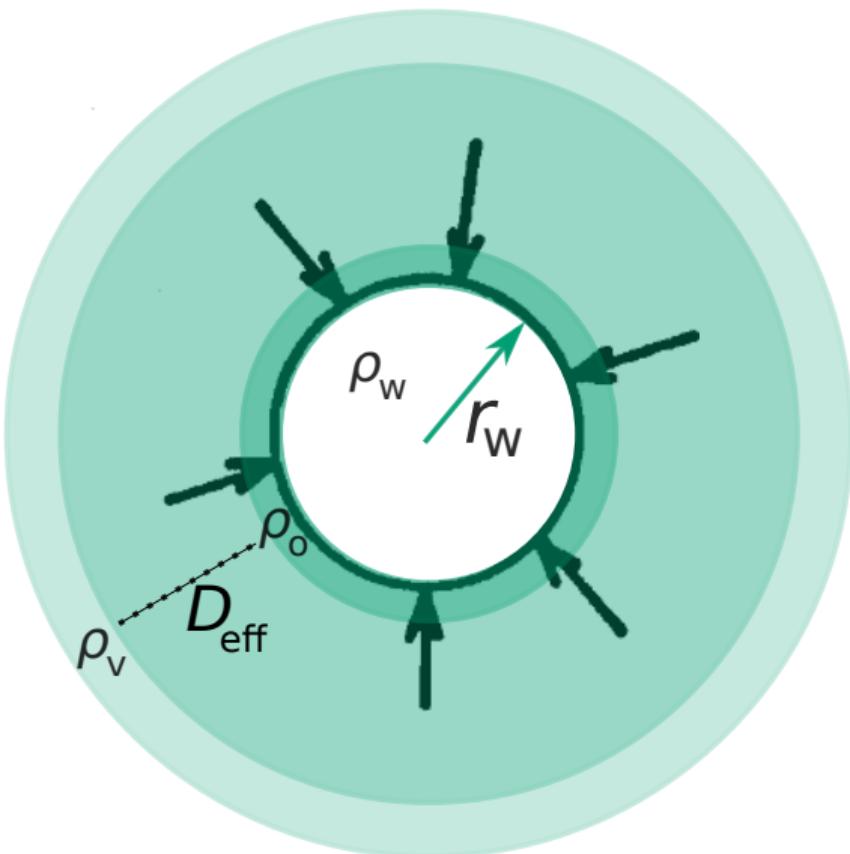
$$\dot{r}_w = \frac{1}{r_w} \frac{D_{\text{eff}}}{\rho_w} (\rho_v - \rho_o)$$

non-dimensional numbers:

$$\text{RH} = \rho_v / \rho_{vs}$$

$$\text{RH}_{\text{eq}} = \rho_o / \rho_{vs}$$

opis kondensacji i parowania kropli: dyfuzja masy i ciepła



Fick's and Fourier's laws combined
spherical geometry

$$\dot{r}_w = \frac{1}{r_w} \frac{D_{\text{eff}}}{\rho_w} (\rho_v - \rho_o)$$

non-dimensional numbers:

$$\text{RH} = \rho_v / \rho_{vs}$$

$$\text{RH}_{\text{eq}} = \rho_o / \rho_{vs}$$

$$\dot{r}_w = \frac{1}{r_w} D_{\text{eff}} \frac{\rho_{vs}}{\rho_w} (\text{RH} - \text{RH}_{\text{eq}})$$

opis kondensacji i parowania kropli: krzywa Köhlera

$$\dot{r}_w = \frac{1}{r_w} D_{\text{eff}} \frac{\rho_{\text{vs}}}{\rho_w} (\text{RH} - \text{RH}_{\text{eq}})$$

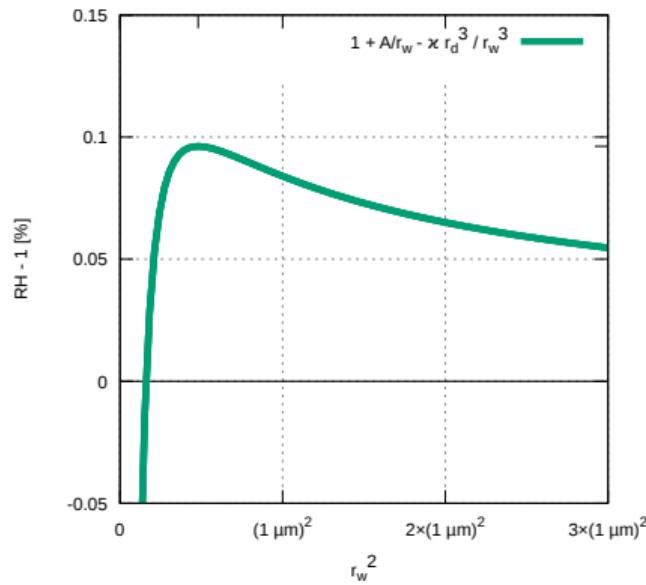
opis kondensacji i parowania kropli: krzywa Köhlera

$$\dot{r}_w = \frac{1}{r_w} D_{\text{eff}} \frac{\rho_{vs}}{\rho_w} (\text{RH} - \text{RH}_{\text{eq}})$$

$$\begin{aligned}\text{RH}_{\text{eq}} &= \frac{r_w^3 - r_d^3}{r_w^3 - r_d^3(1 - \kappa)} \exp\left(\frac{A}{r_w}\right) \\ &\approx 1 + \frac{A}{r_w} - \frac{\kappa r_d^3}{r_w^3}\end{aligned}$$

opis kondensacji i parowania kropli: krzywa Köhlera

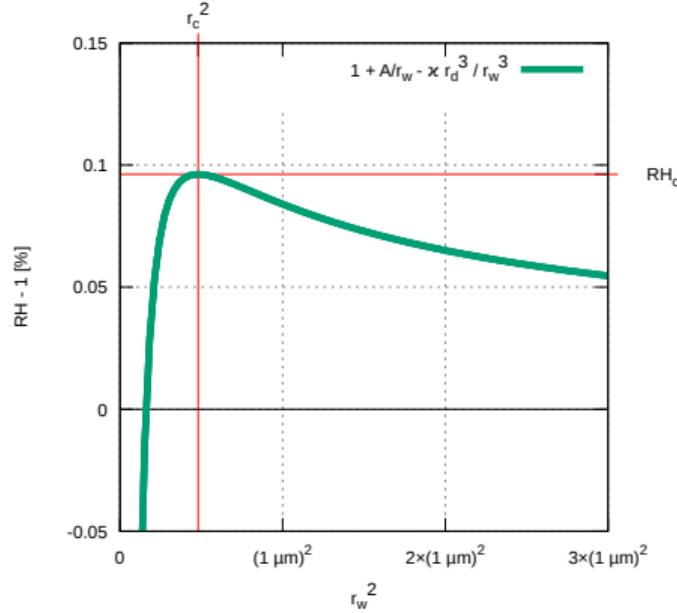
$$\dot{r}_w = \frac{1}{r_w} D_{\text{eff}} \frac{\rho_{\text{vs}}}{\rho_w} (\text{RH} - \text{RH}_{\text{eq}})$$



$$\begin{aligned}\text{RH}_{\text{eq}} &= \frac{r_w^3 - r_d^3}{r_w^3 - r_d^3(1 - \kappa)} \exp\left(\frac{A}{r_w}\right) \\ &\approx 1 + \frac{A}{r_w} - \frac{\kappa r_d^3}{r_w^3}\end{aligned}$$

opis kondensacji i parowania kropli: krzywa Köhlera

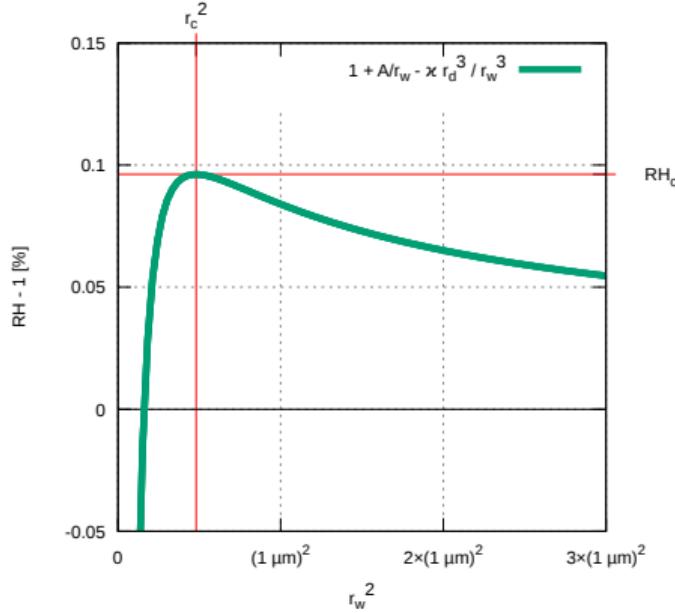
$$\dot{r}_w = \frac{1}{r_w} D_{\text{eff}} \frac{\rho_{\text{vs}}}{\rho_w} (\text{RH} - \text{RH}_{\text{eq}})$$



$$\begin{aligned}\text{RH}_{\text{eq}} &= \frac{r_w^3 - r_d^3}{r_w^3 - r_d^3(1 - \kappa)} \exp\left(\frac{A}{r_w}\right) \\ &\approx 1 + \frac{A}{r_w} - \frac{\kappa r_d^3}{r_w^3}\end{aligned}$$

opis kondensacji i parowania kropli: krzywa Köhlera

$$\dot{r}_w = \frac{1}{r_w} D_{\text{eff}} \frac{\rho_{\text{vs}}}{\rho_w} (\text{RH} - \text{RH}_{\text{eq}})$$



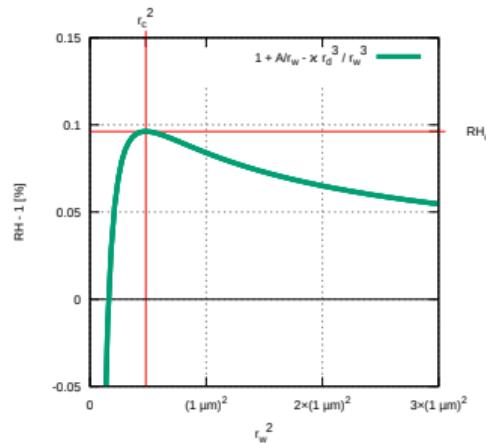
$$\begin{aligned}\text{RH}_{\text{eq}} &= \frac{r_w^3 - r_d^3}{r_w^3 - r_d^3(1 - \kappa)} \exp\left(\frac{A}{r_w}\right) \\ &\approx 1 + \frac{A}{r_w} - \frac{\kappa r_d^3}{r_w^3}\end{aligned}$$

maximum at (r_c, RH_c) :

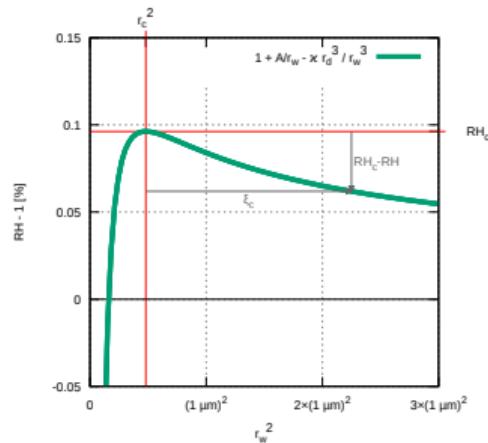
$$r_c = \sqrt{3\kappa r_d^3/A}$$

$$\text{RH}_c = 1 + \frac{2A}{3r_c}$$

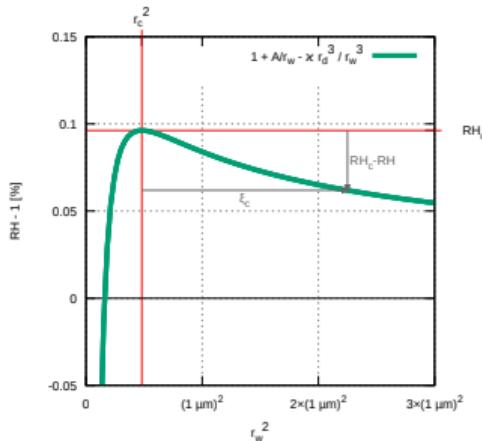
portret fazowy układu (odwrócona krzywa Köhlera)



portret fazowy układu (odwrócona krzywa Köhlera)



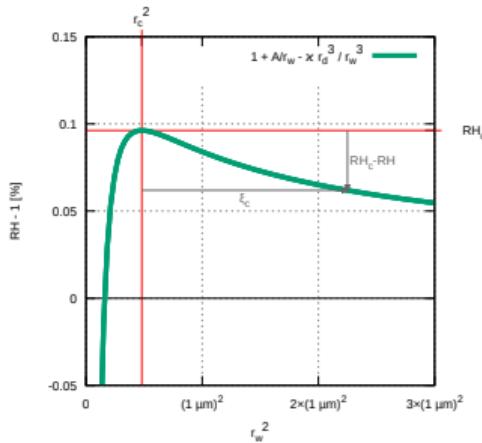
portret fazowy układu (odwrócona krzywa Köhlera)



$$\xi = r_w^2 + C$$

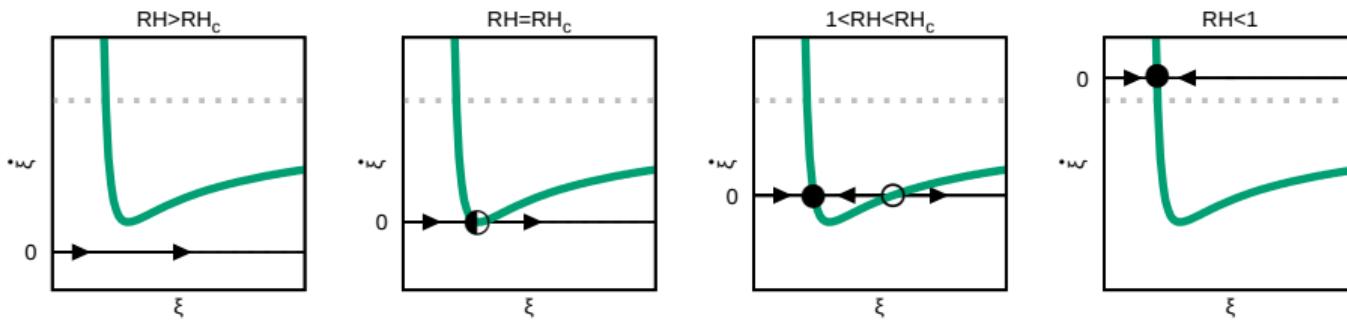
$$\dot{\xi} = 2D_{\text{eff}} \frac{\rho_{\text{vs}}}{\rho_w} (RH - RH_{\text{eq}}(\xi))$$

portret fazowy układu (odwrócona krzywa Köhlera)



$$\xi = r_w^2 + C$$

$$\dot{\xi} = 2D_{\text{eff}} \frac{\rho_{\text{vs}}}{\rho_w} (RH - RH_{\text{eq}}(\xi))$$



oddziaływanie aerozol – chmury – opad: zjawiska



- ❑ aktywacja kropelek na aerozolu
- ❑ kondensacja

oddziaływanie aerozol – chmury – opad: zjawiska



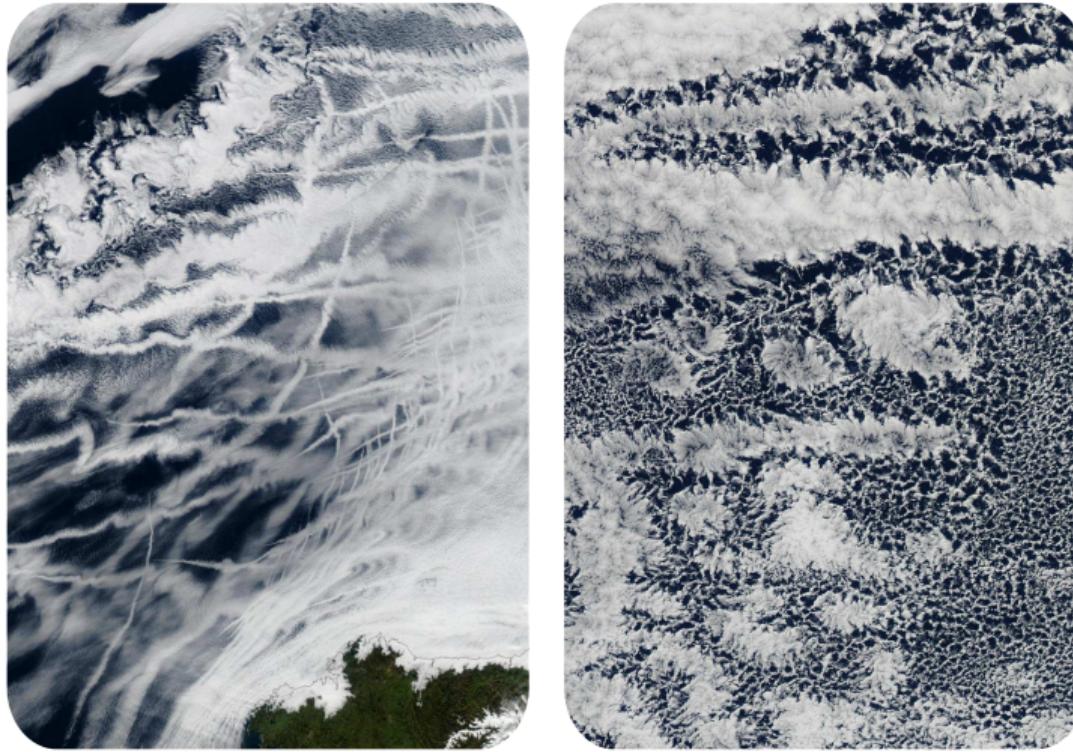
- aktywacja kropelek na aerozolu
- kondensacja
- zderzenia pomiędzy kropelkami
- procesy chemiczne zachodzące w kropelkach

oddziaływanie aerozol – chmury – opad: zjawiska



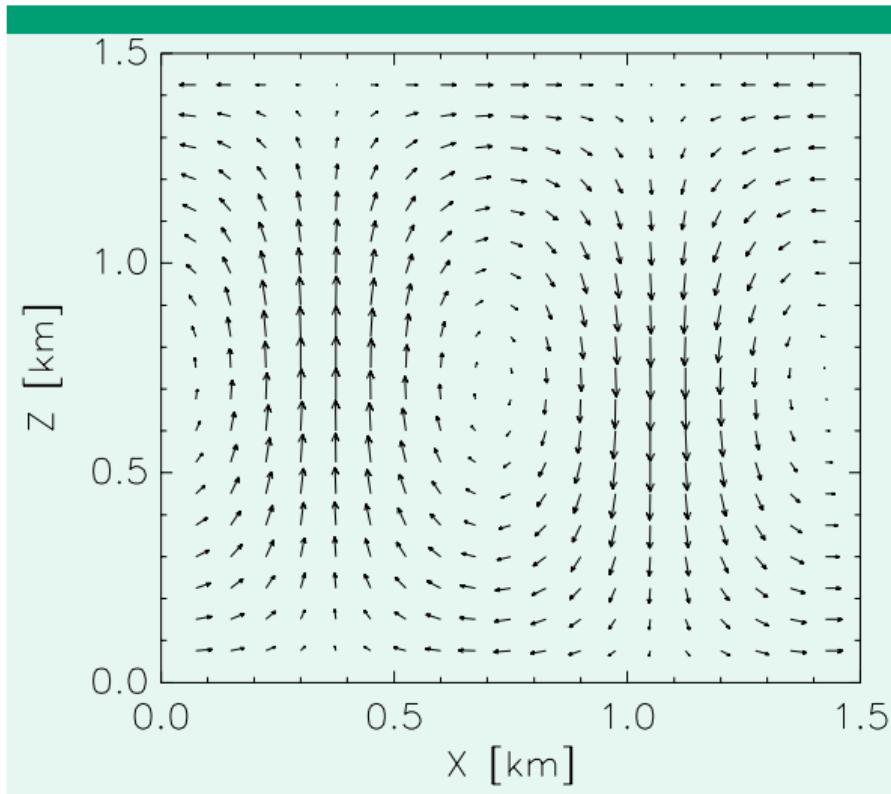
- ❖ aktywacja kropelek na aerozolu
- ❖ kondensacja
- ❖ zderzenia pomiędzy kropelkami
- ❖ procesy chemiczne zachodzące w kropelkach
- ❖ opad
- ❖ wymywanie aerozolu
- ❖ odparowywanie kropelek

oddziaływanie aerozol – chmury – aerozol: przykłady

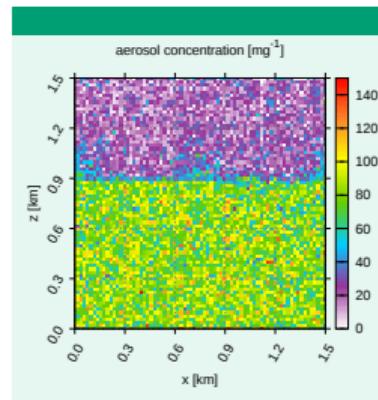
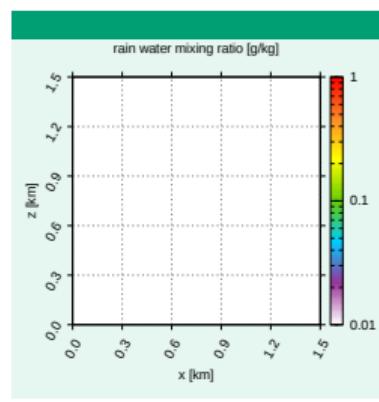
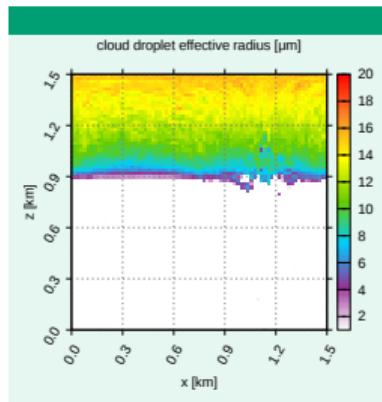
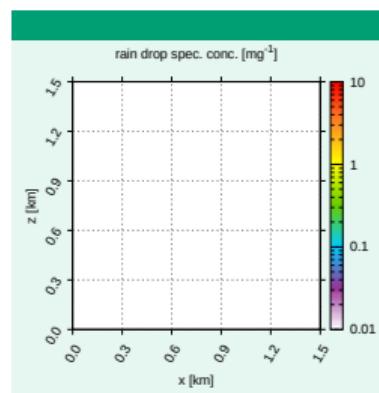
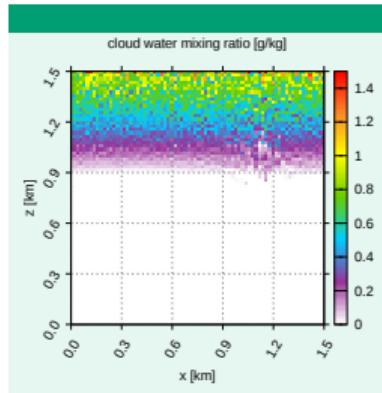


źródło: NASA (27 I 2003 – Zatoka Biskajskia; 17 IV 2010 – Pacyfik u wybrzeży Peru)

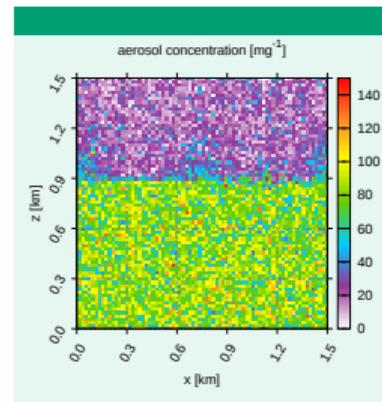
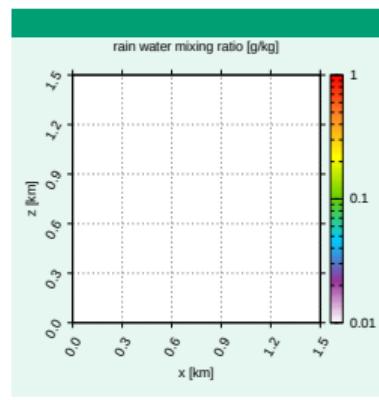
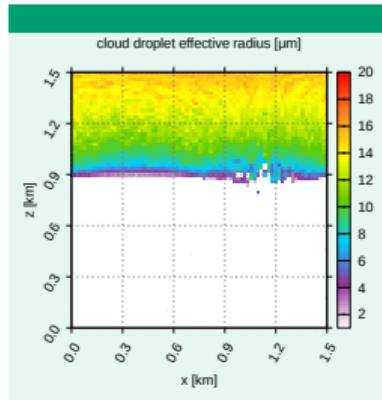
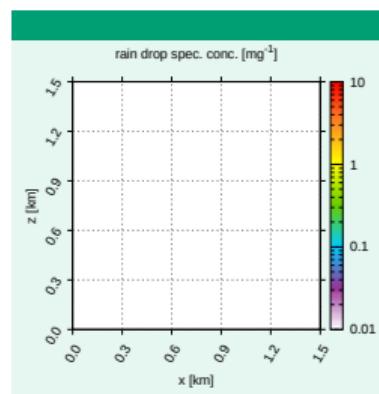
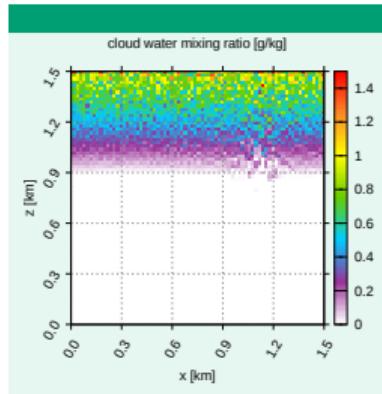
przykładowa symulacja chmury (2D)



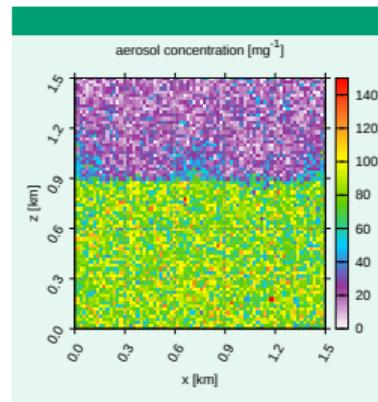
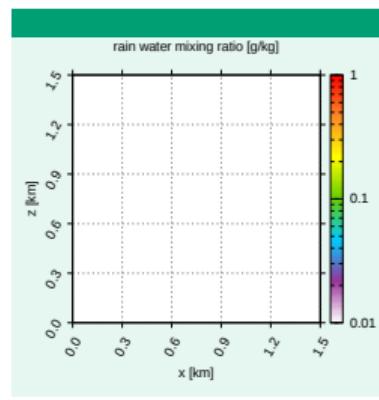
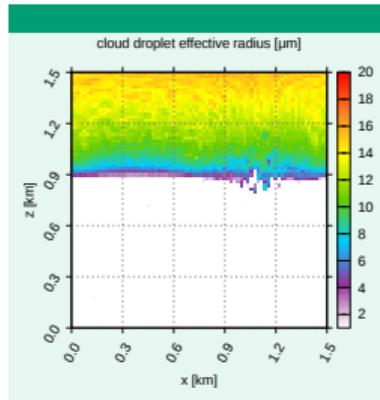
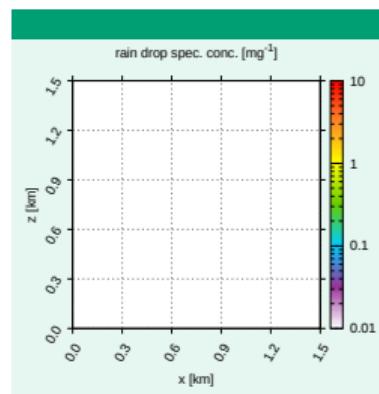
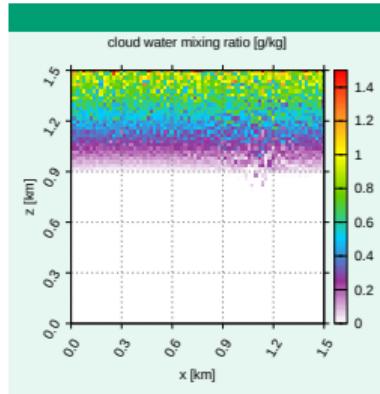
przykładowa symulacja chmury (2D)



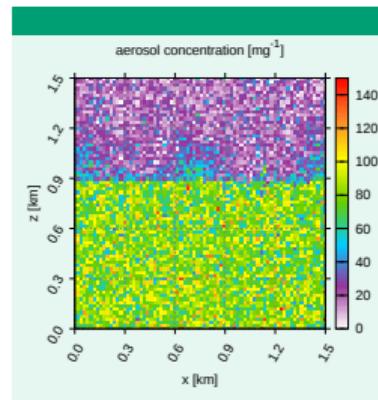
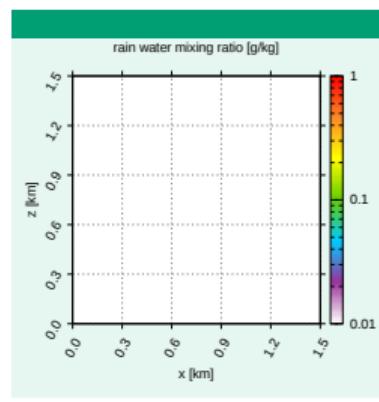
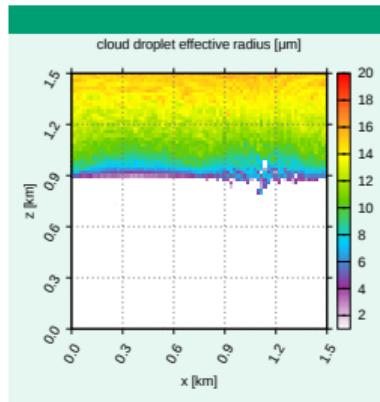
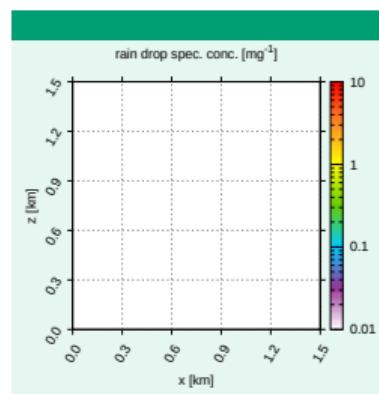
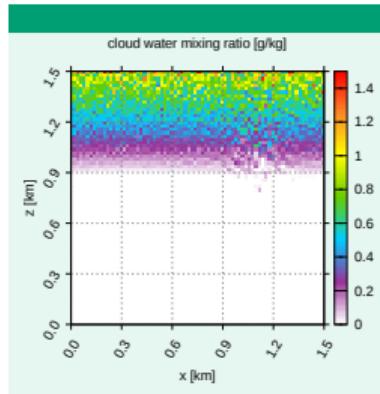
przykładowa symulacja chmury (2D)



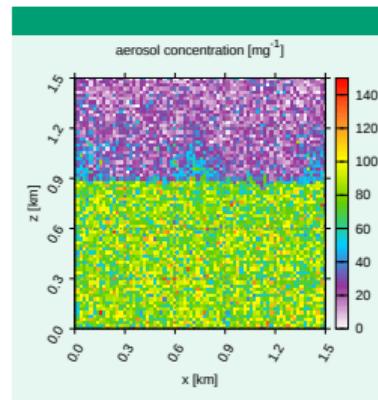
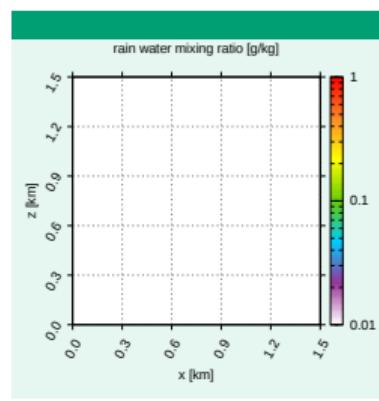
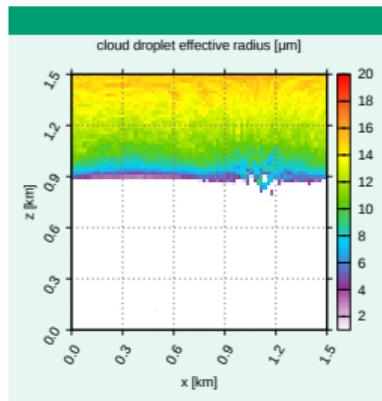
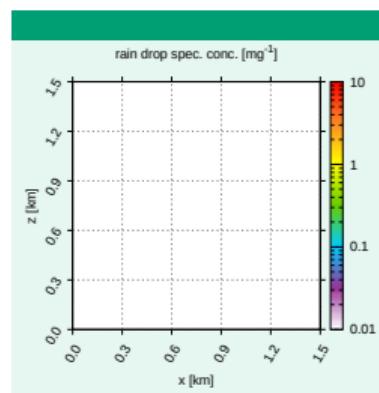
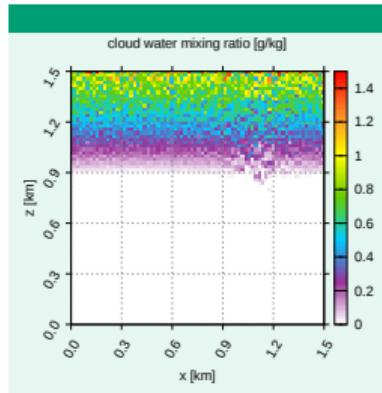
przykładowa symulacja chmury (2D)



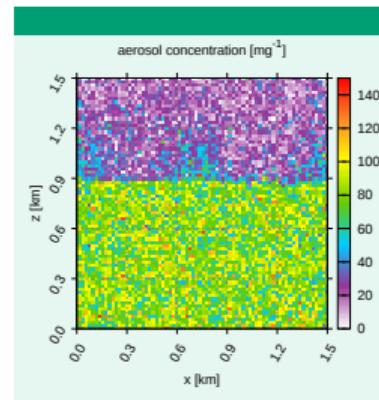
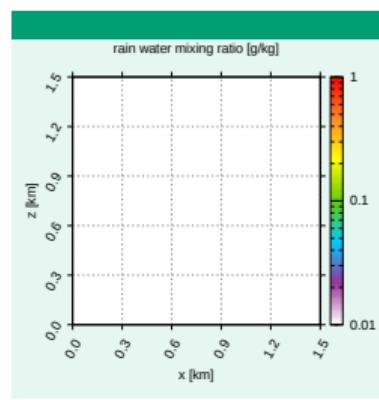
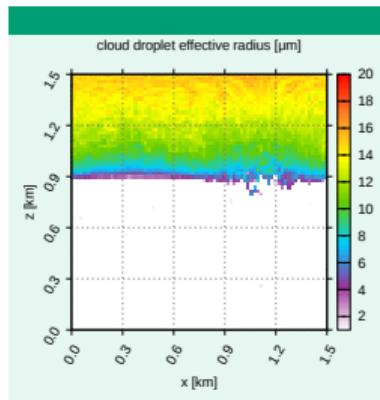
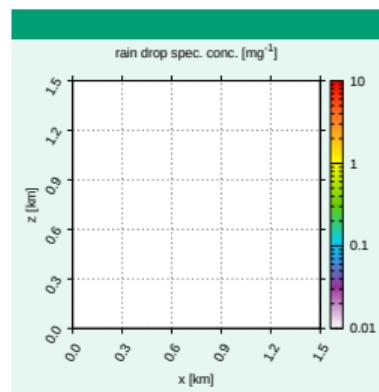
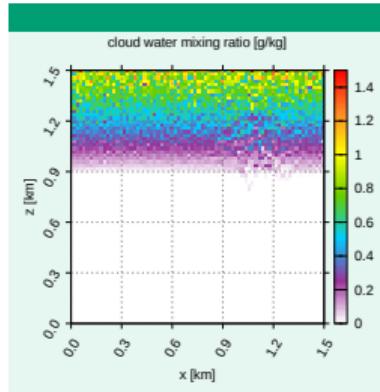
przykładowa symulacja chmury (2D)



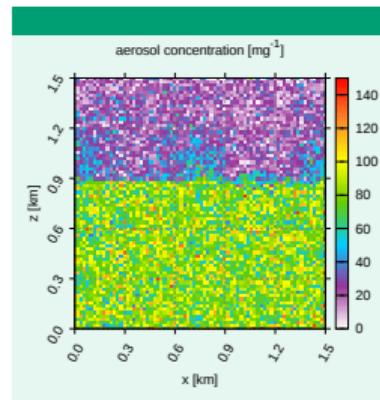
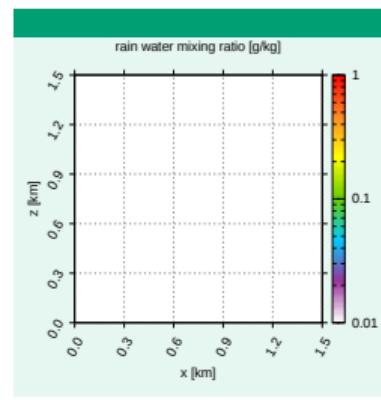
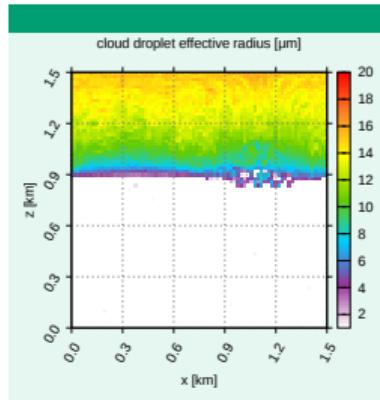
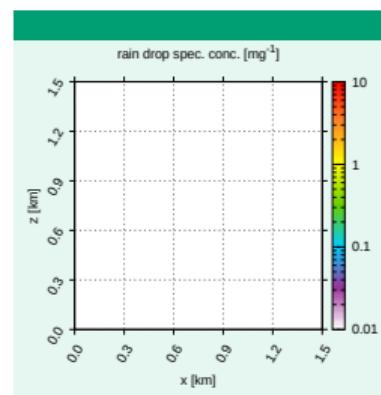
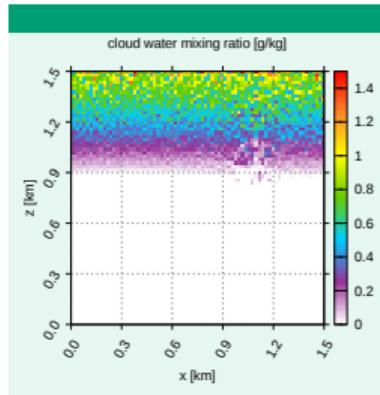
przykładowa symulacja chmury (2D)



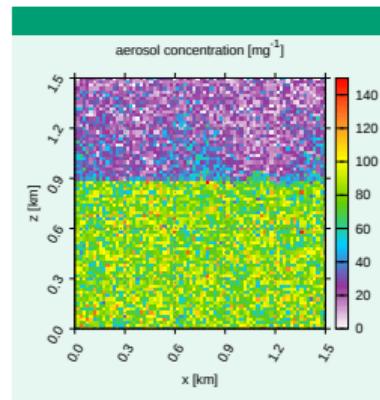
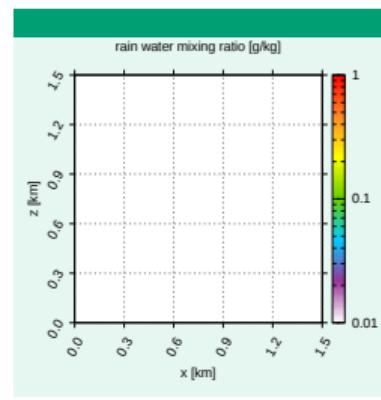
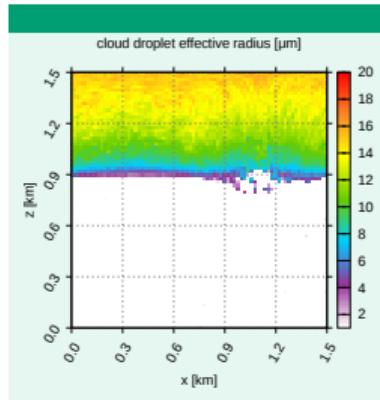
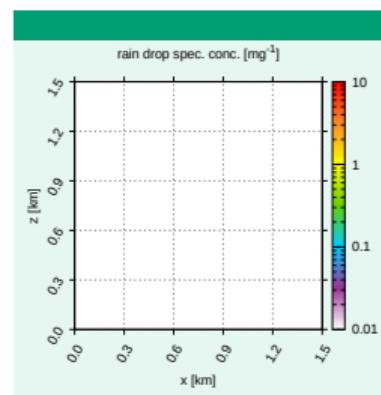
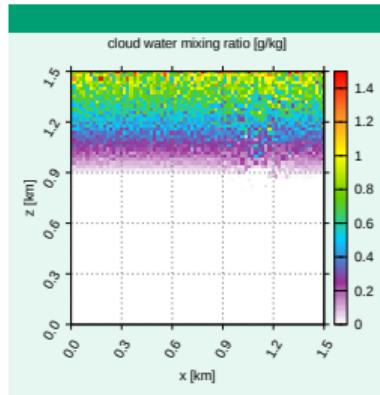
przykładowa symulacja chmury (2D)



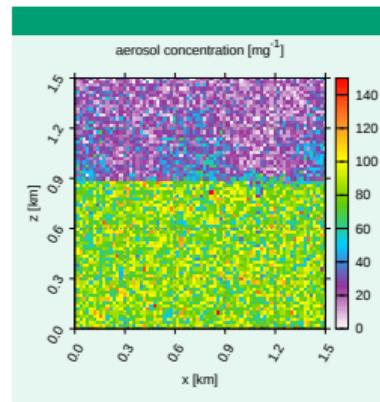
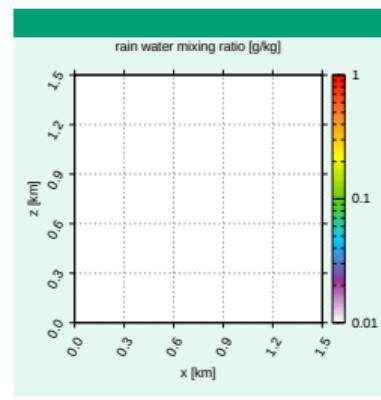
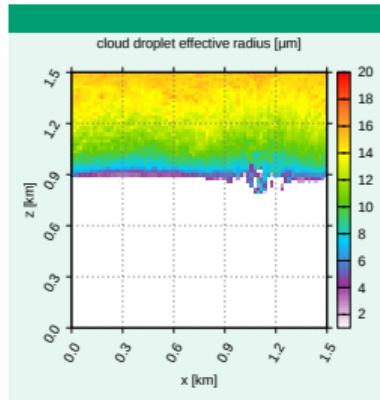
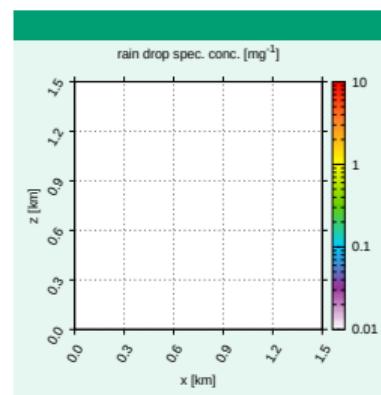
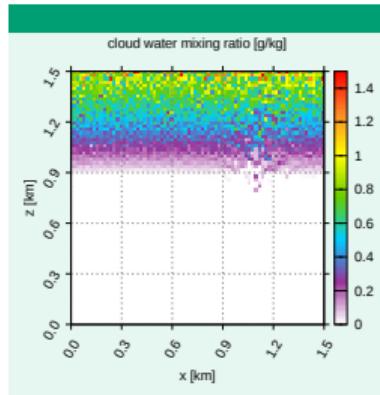
przykładowa symulacja chmury (2D)



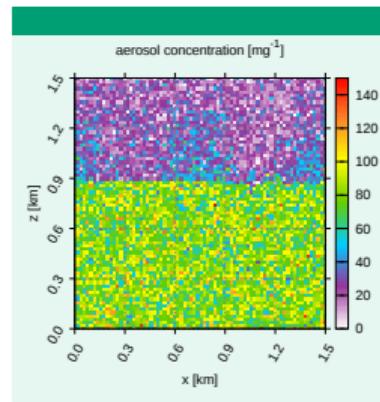
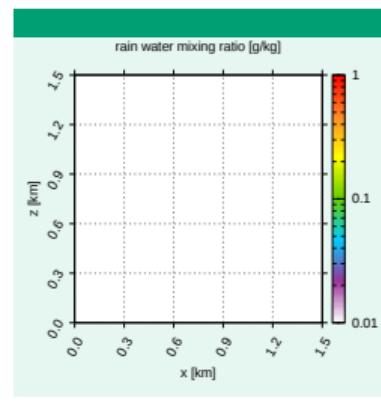
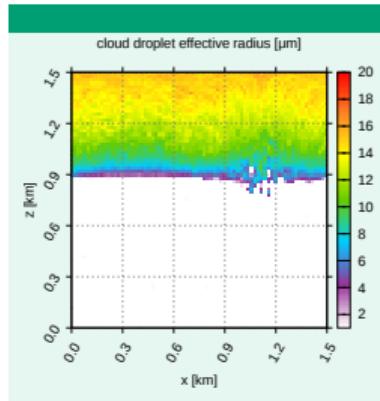
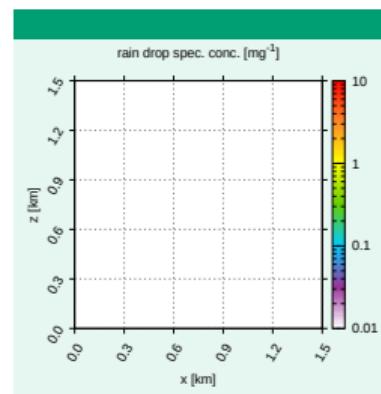
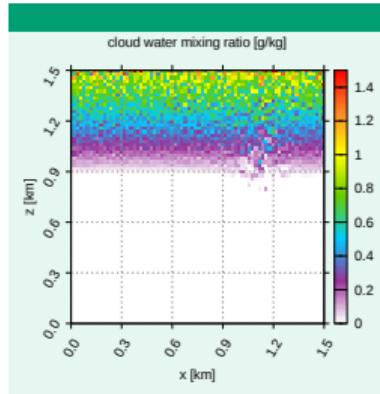
przykładowa symulacja chmury (2D)



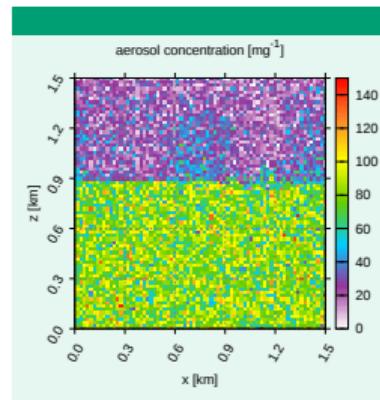
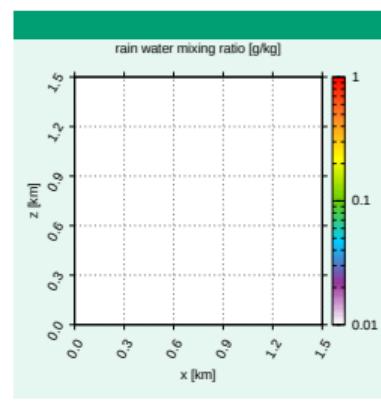
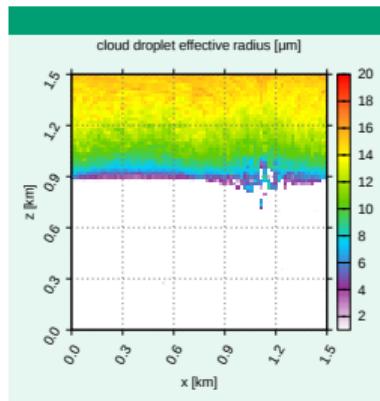
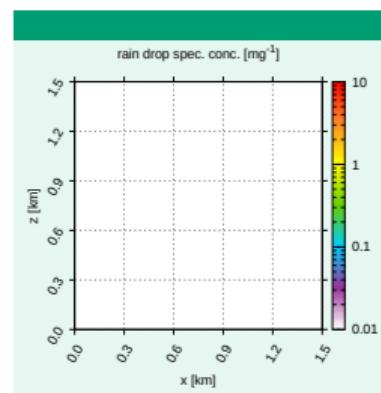
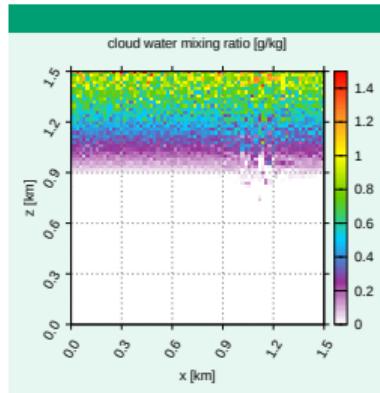
przykładowa symulacja chmury (2D)



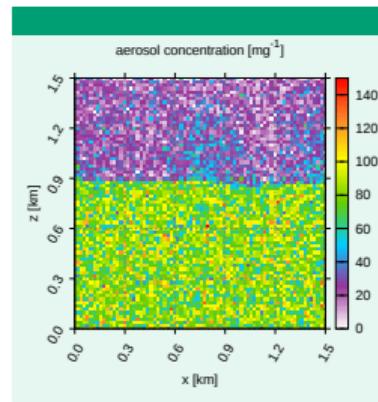
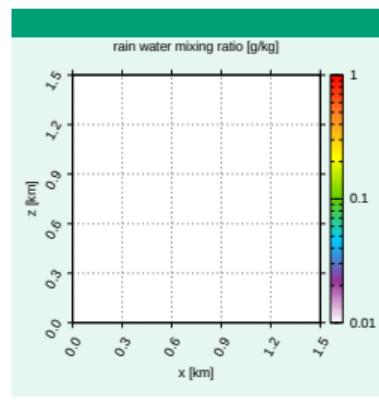
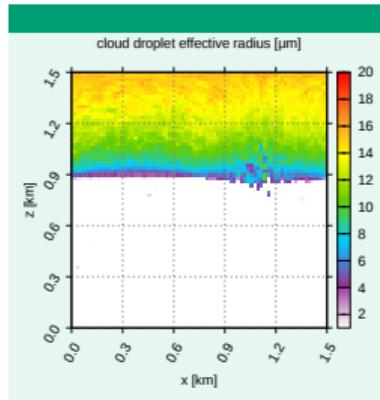
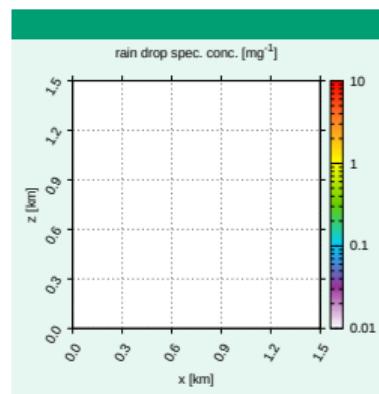
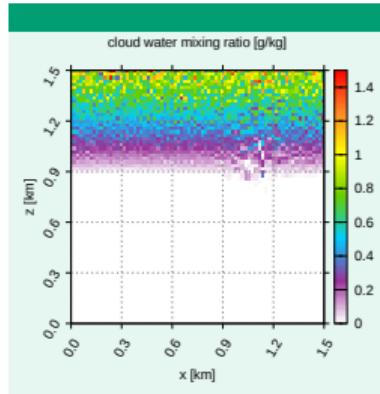
przykładowa symulacja chmury (2D)



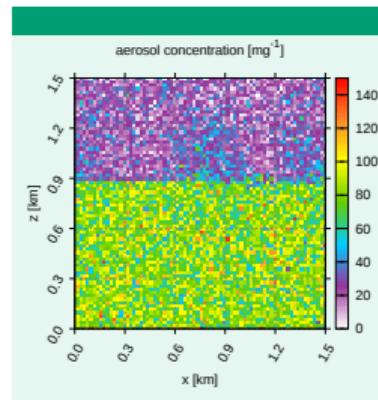
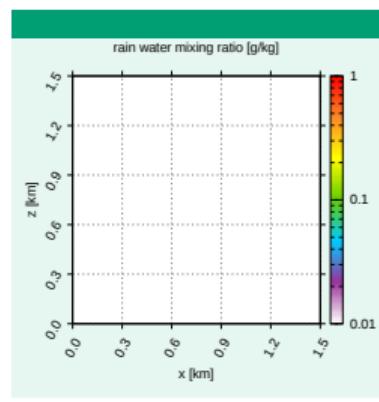
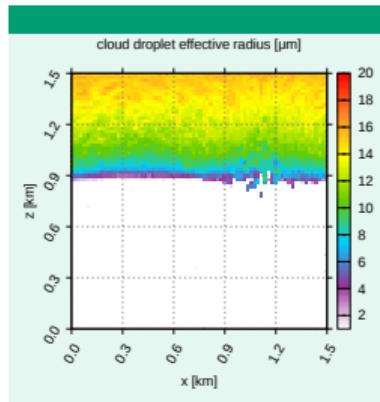
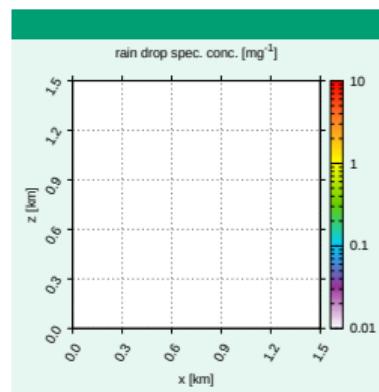
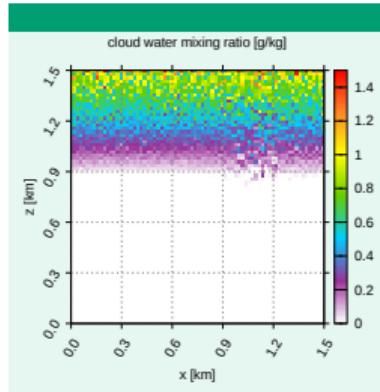
przykładowa symulacja chmury (2D)



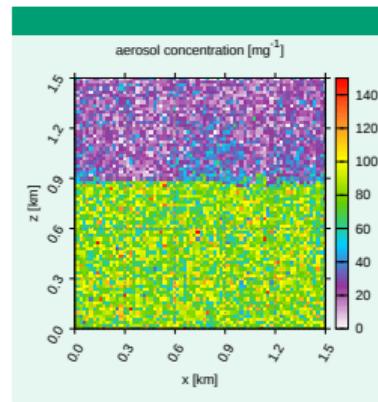
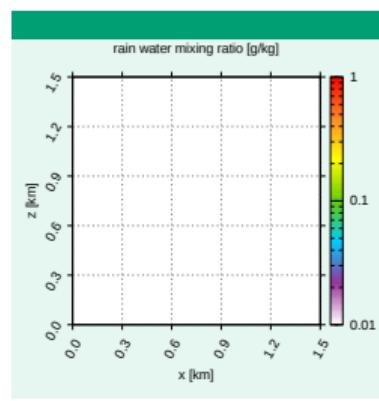
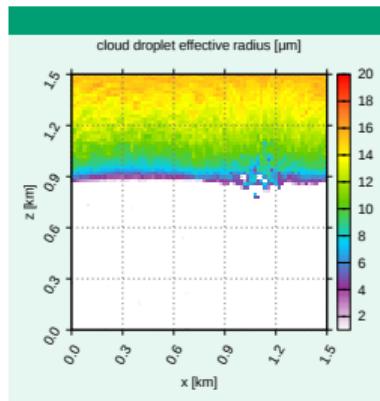
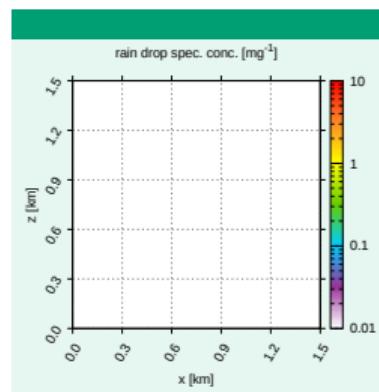
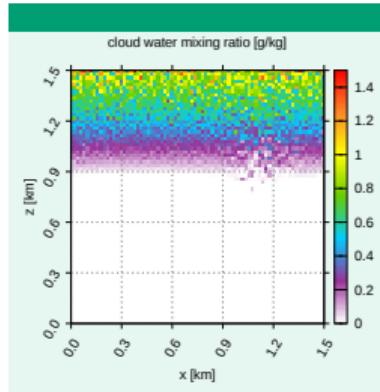
przykładowa symulacja chmury (2D)



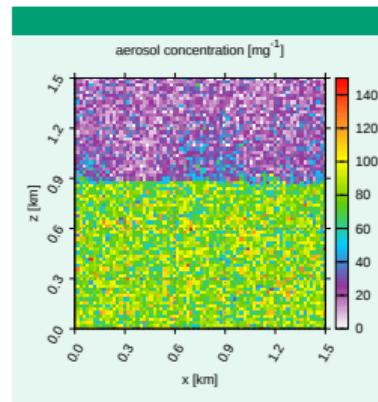
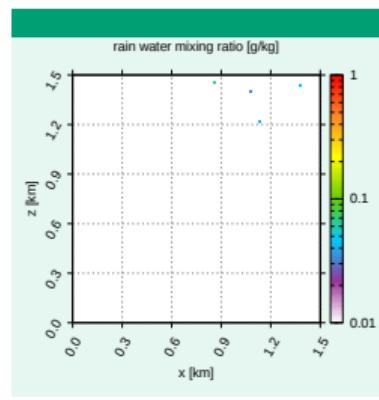
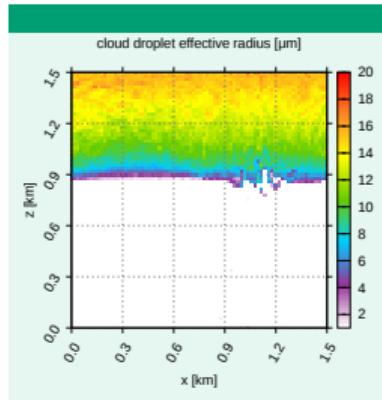
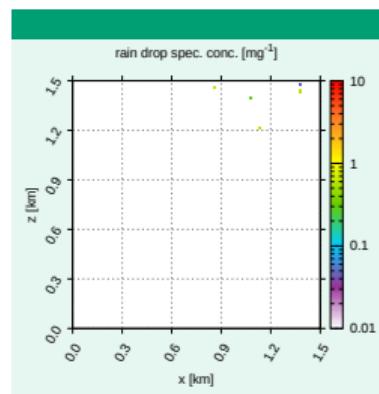
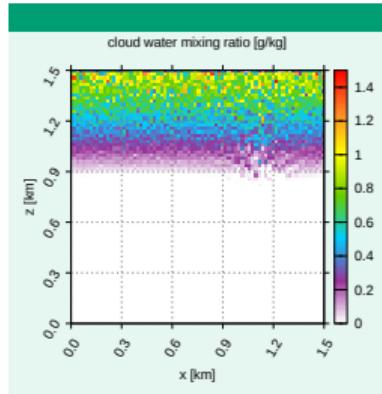
przykładowa symulacja chmury (2D)



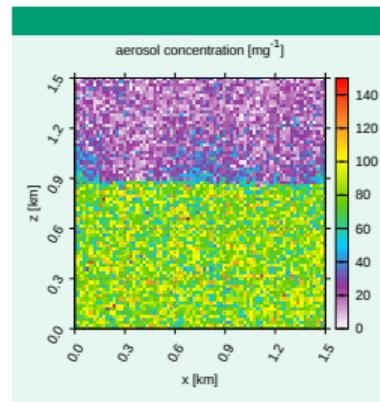
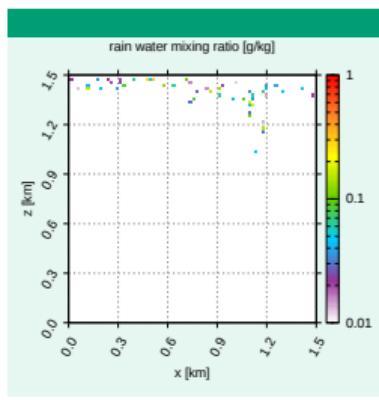
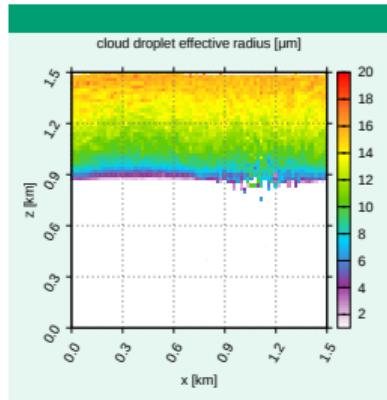
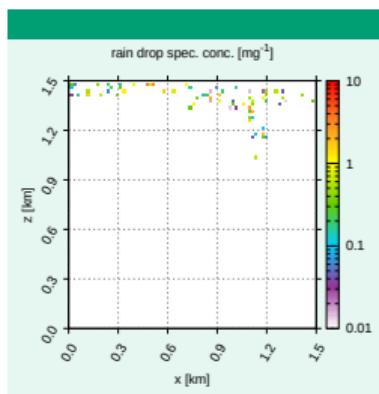
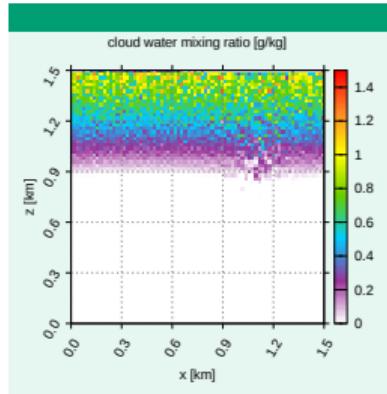
przykładowa symulacja chmury (2D)



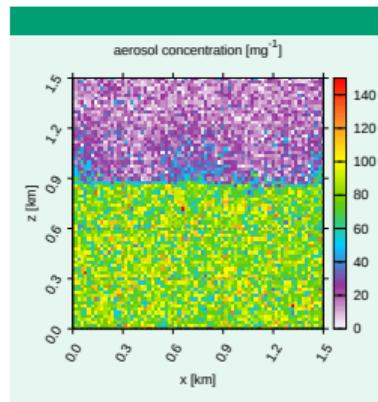
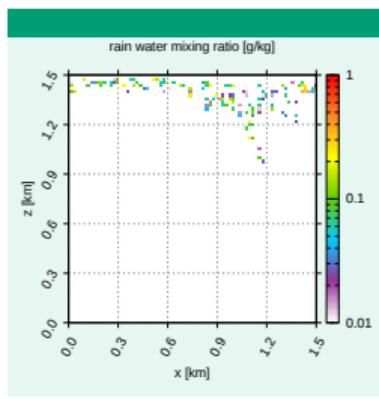
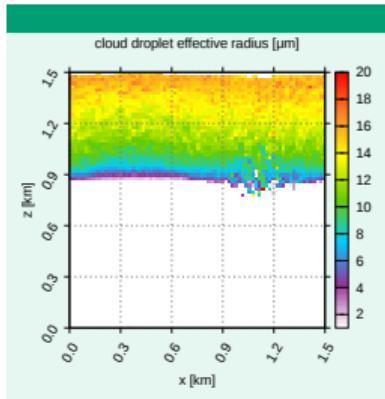
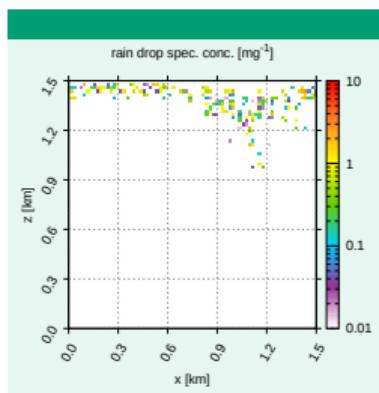
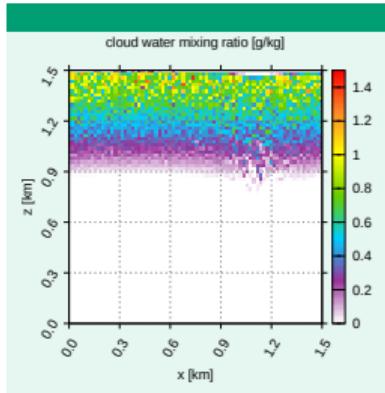
przykładowa symulacja chmury (2D)



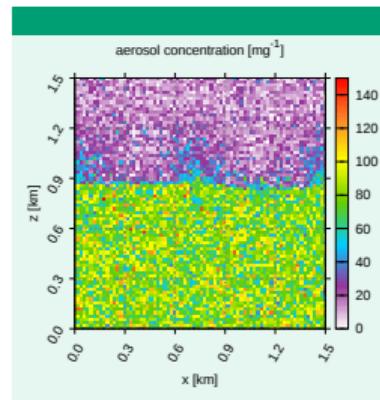
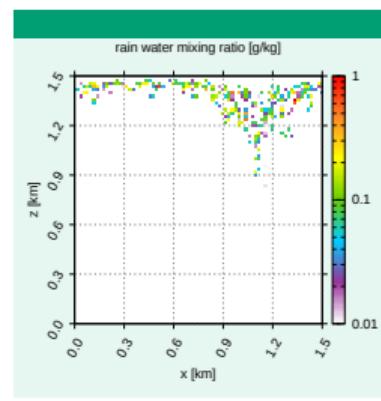
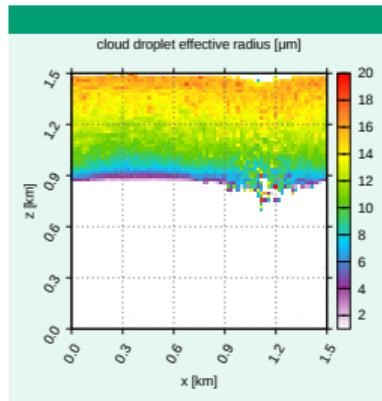
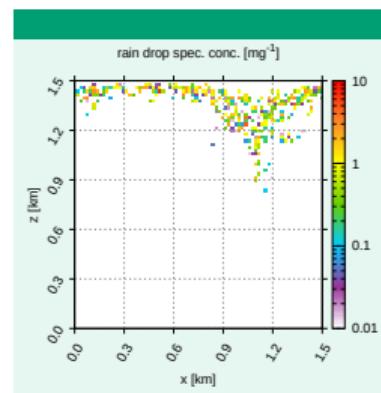
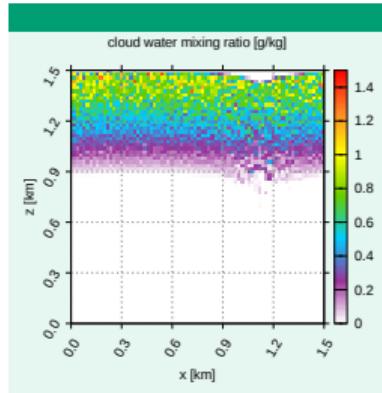
przykładowa symulacja chmury (2D)



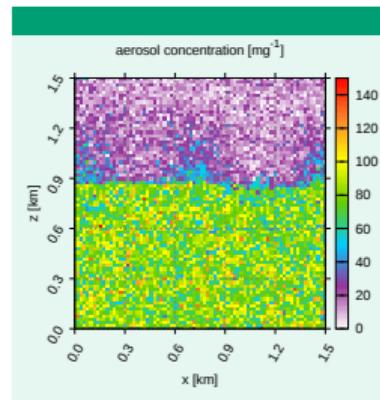
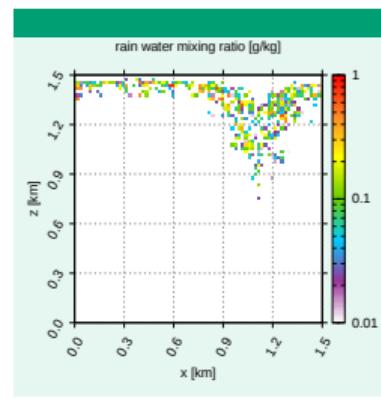
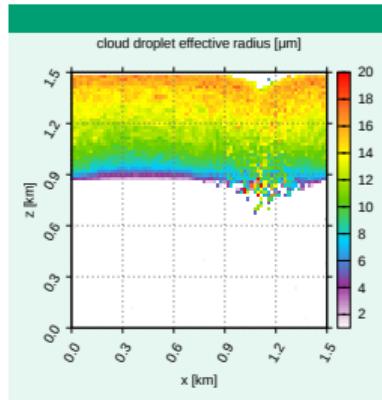
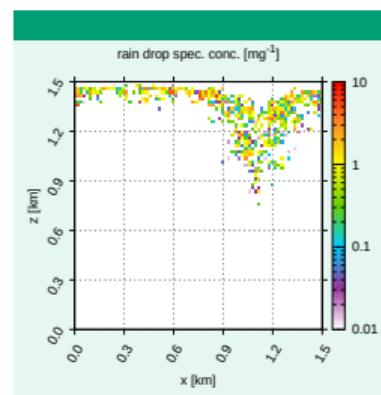
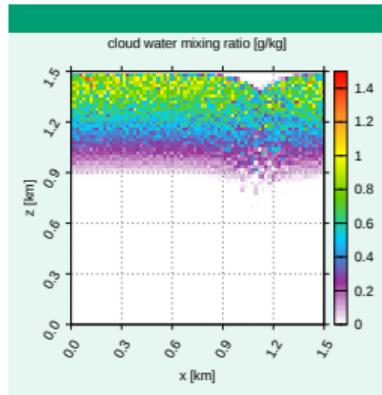
przykładowa symulacja chmury (2D)



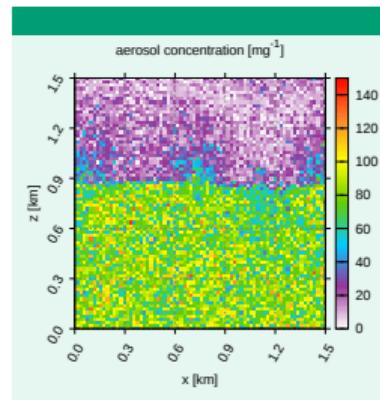
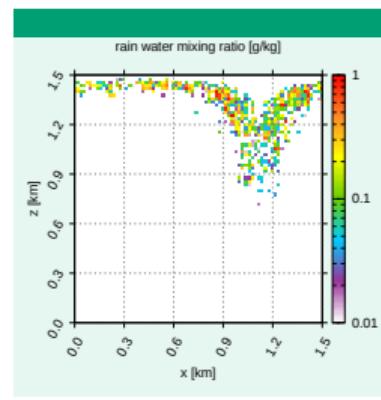
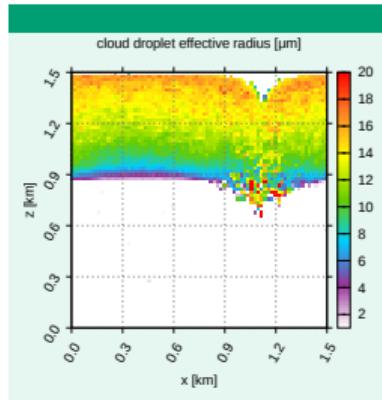
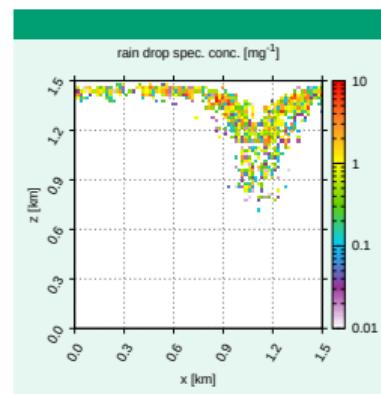
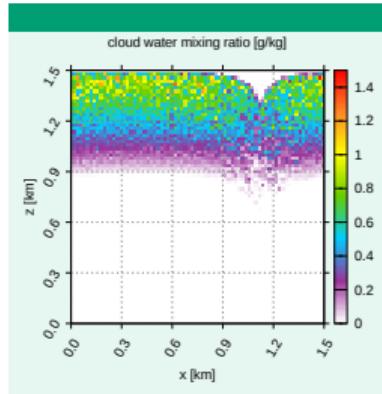
przykładowa symulacja chmury (2D)



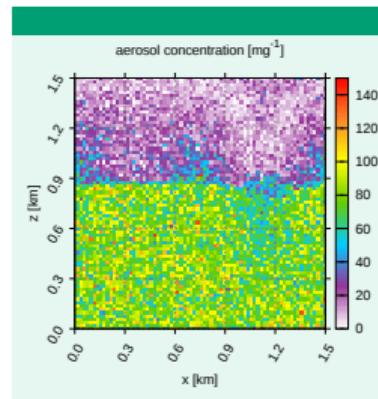
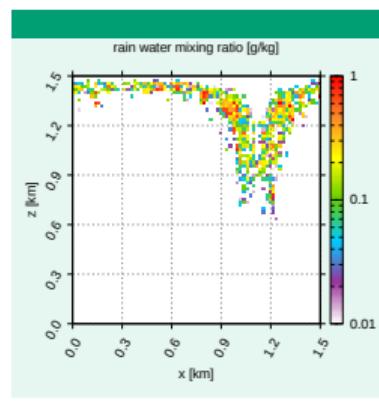
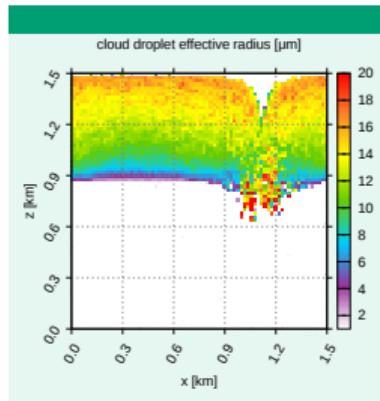
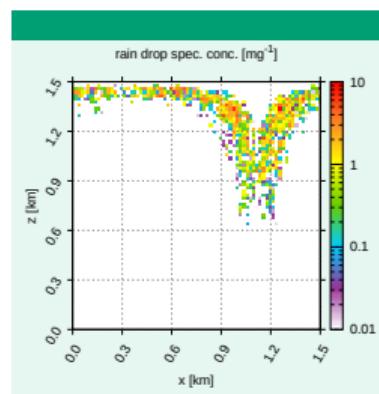
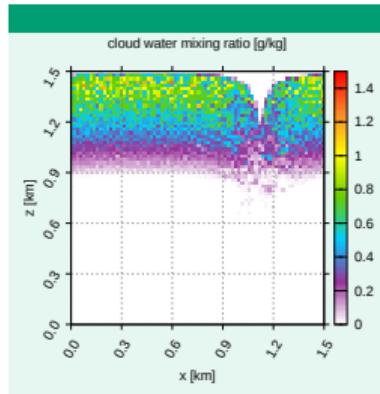
przykładowa symulacja chmury (2D)



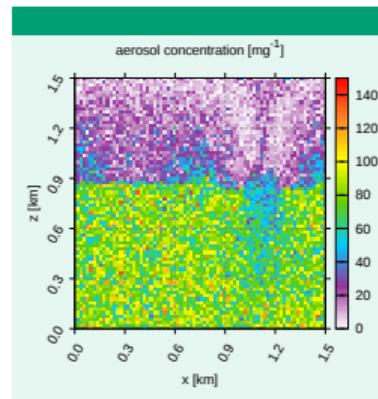
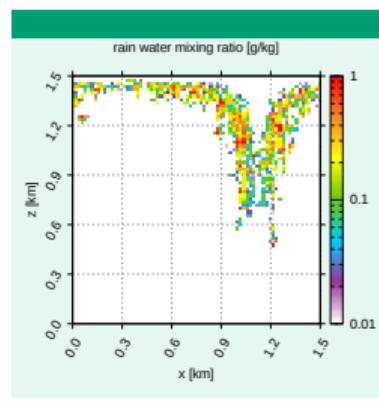
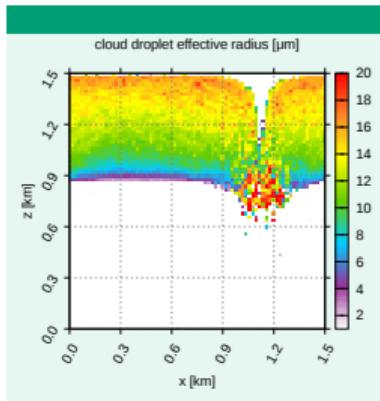
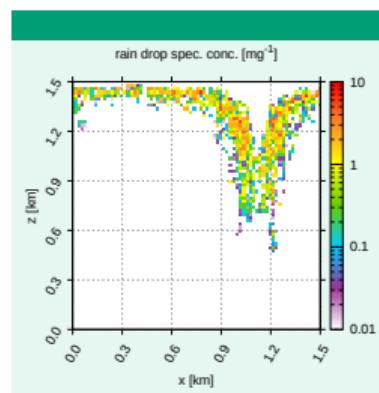
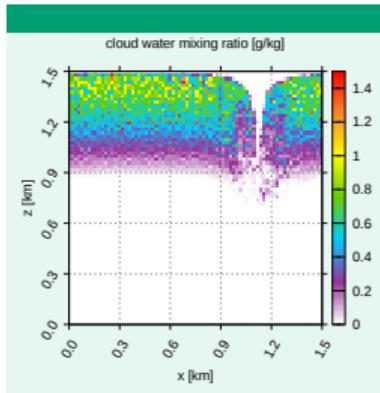
przykładowa symulacja chmury (2D)



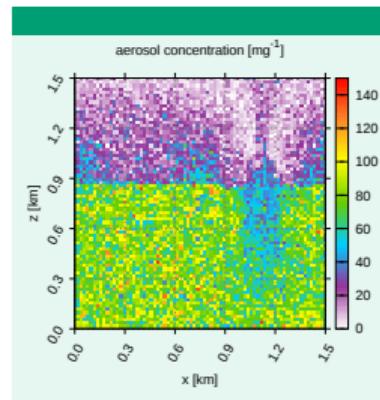
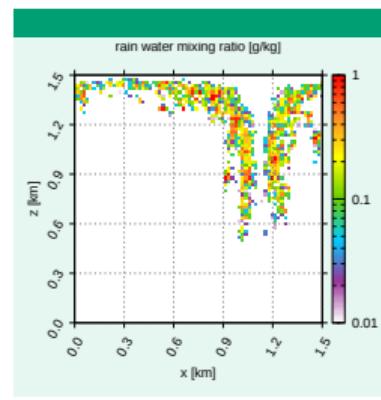
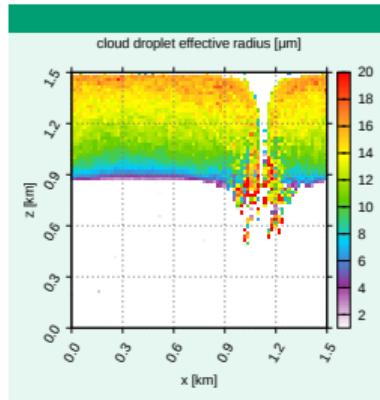
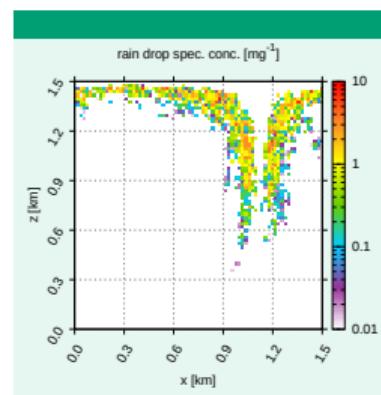
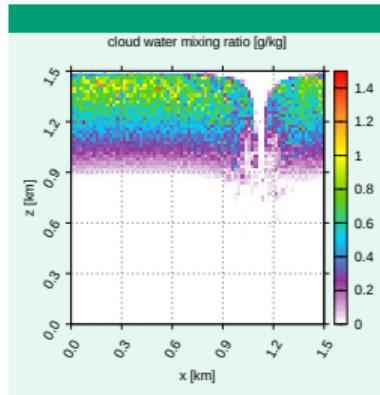
przykładowa symulacja chmury (2D)



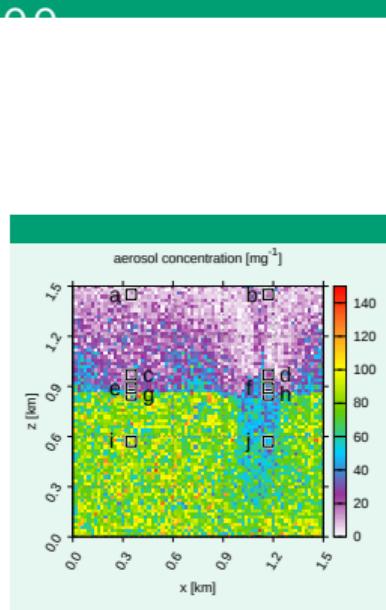
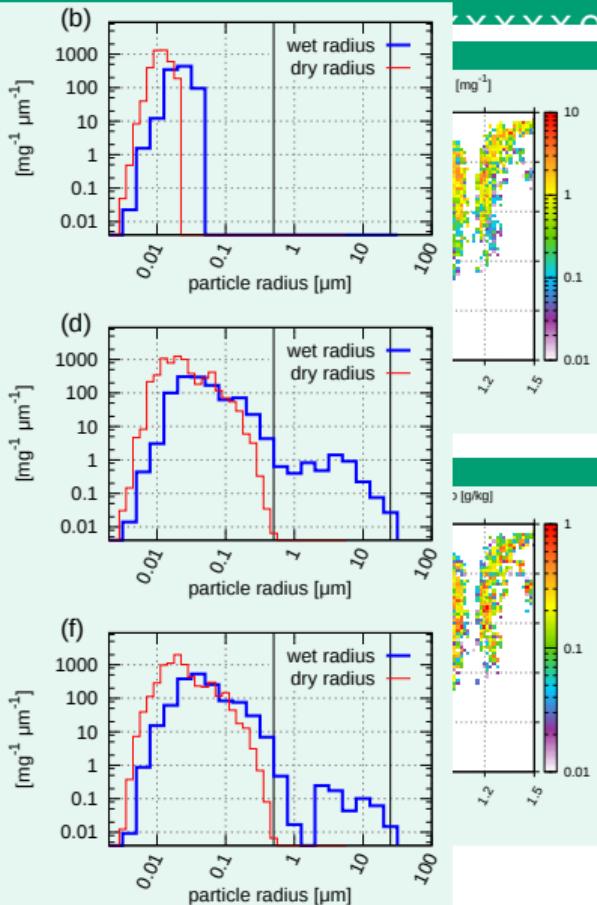
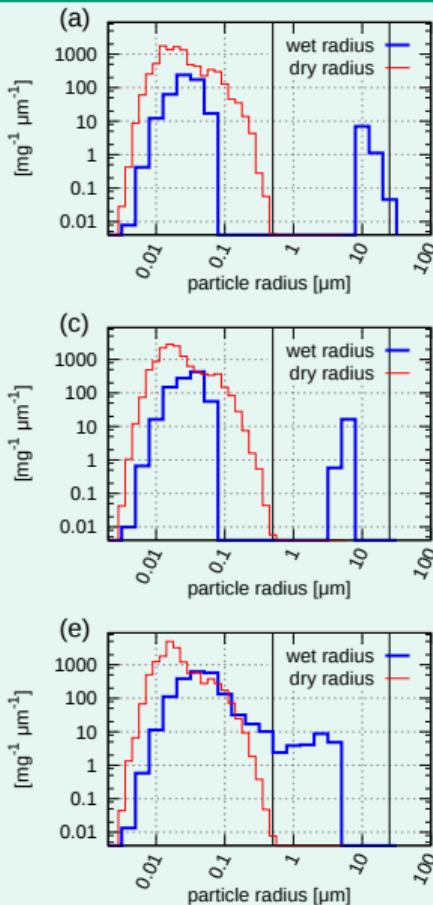
przykładowa symulacja chmury (2D)



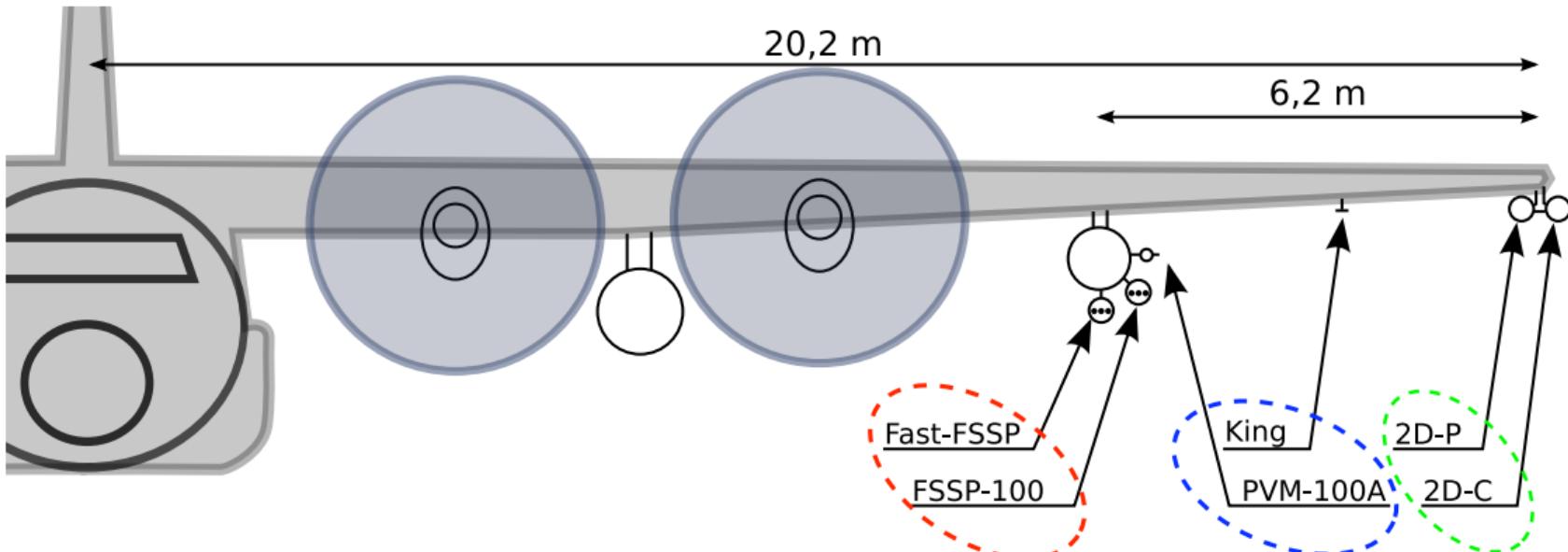
przykładowa symulacja chmury (2D)



widma rozmiarów cząstek



pomiary chmur z pokładu samolotu NSF/NCAR C-130Q podczas RICO



- 19 ok. 8-godzinnych lotów badawczych
- 5–10% czasu lotu wewnętrz chmur
- loty nad powierzchnią oceanu
- spektrometria rozmiarów kropel chmurowych
- pomiary całkowej zawartości wody
- spektrometria rozmiarów kropel opadowych



Instrumenty FSSP-100 i FSSP-300 przymocowane pod skrzydłem samolotu M55 Geophysica. (Wagadugu, Burkina Faso, 2006; fot. autor)

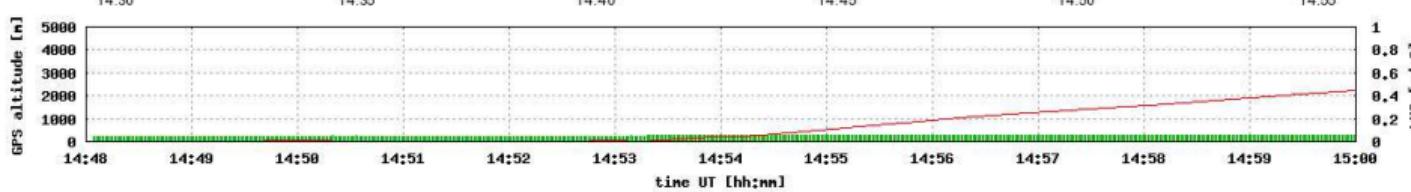
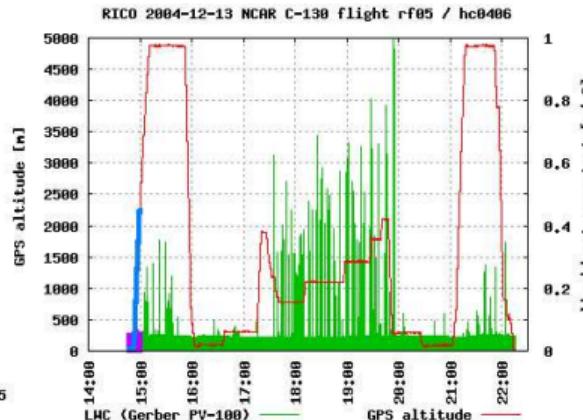
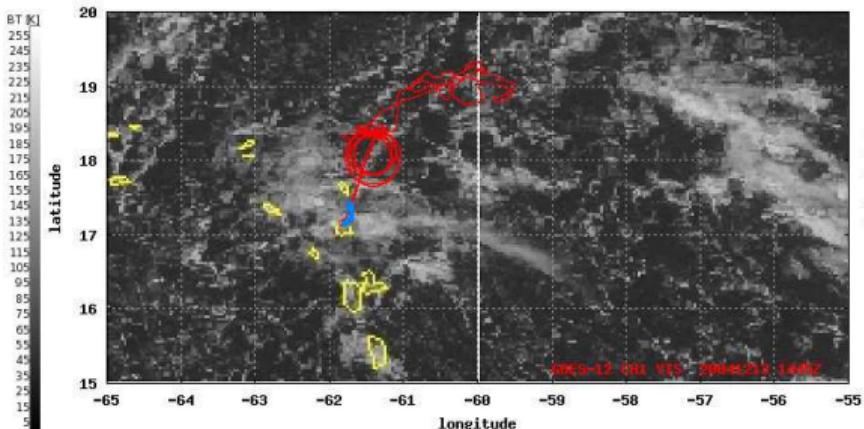


Instrument King-probe przymocowany do kadłuba samolotu ATR-42. (Jassy, Rumunia, 2007; fot. autor)

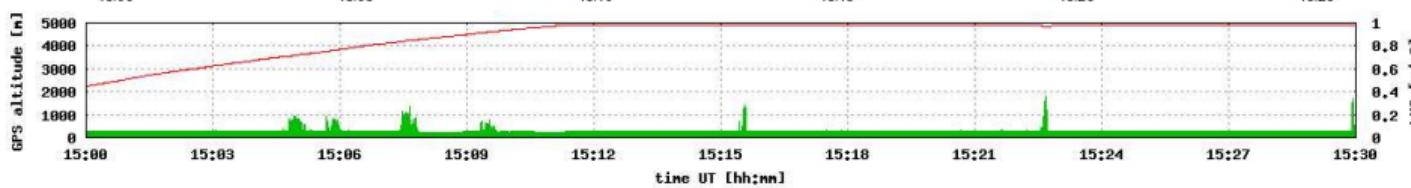
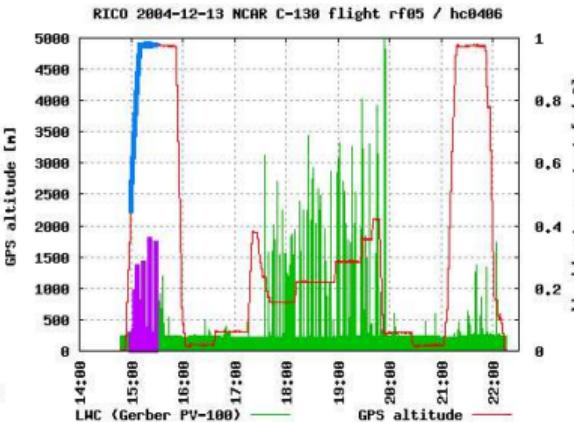
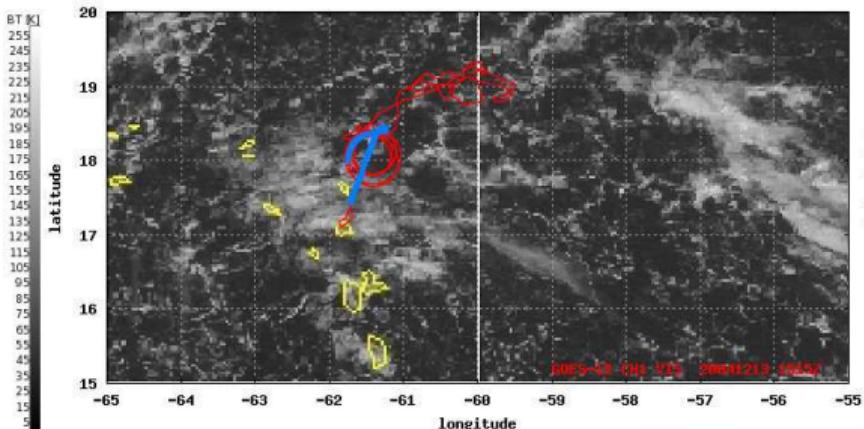


Instrument PVM-100A przymocowany do kadłuba samolotu ATR-42 (Jassy, Rumunia, 2007; fot. autor)

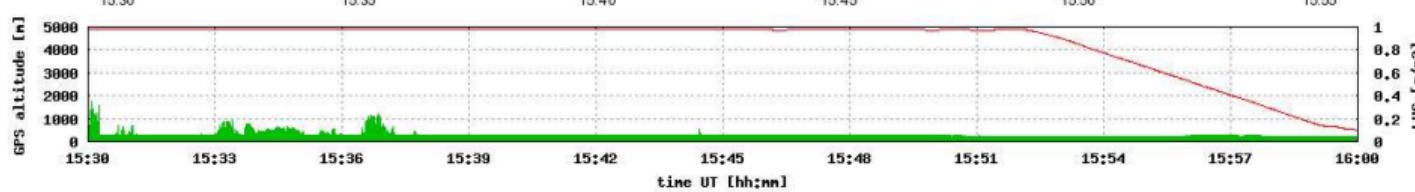
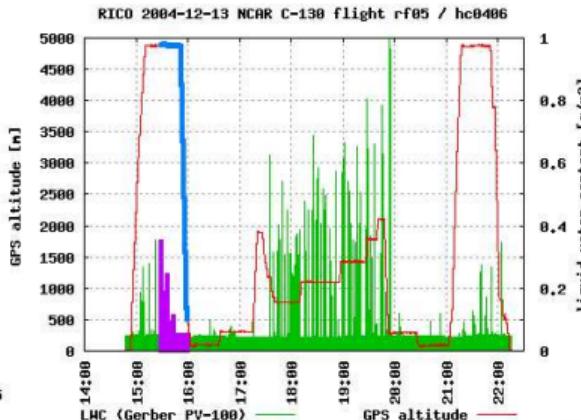
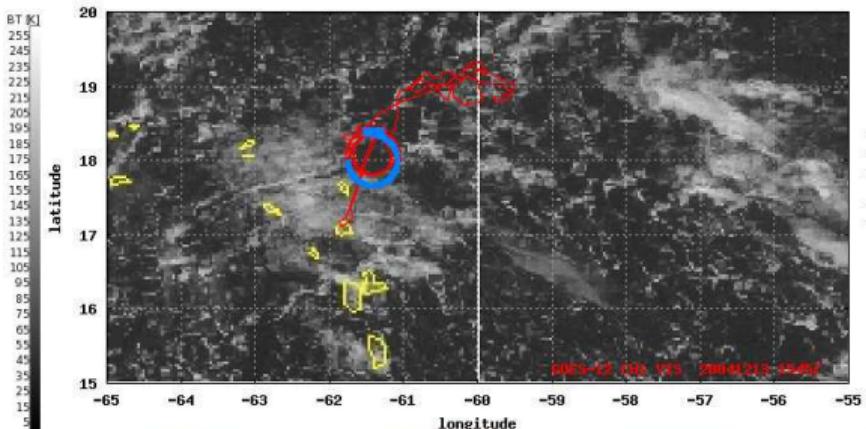
lot badawczy RICO: C-130 RF05



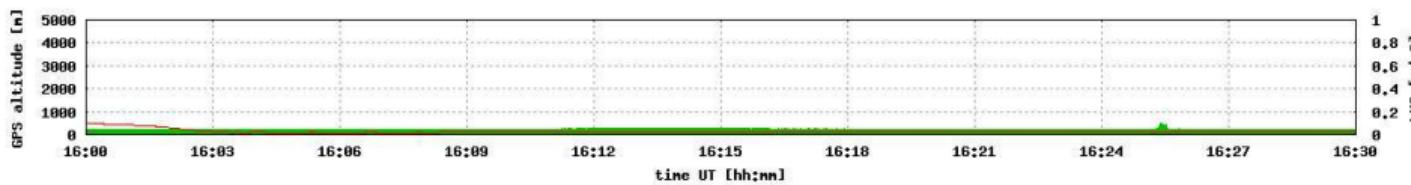
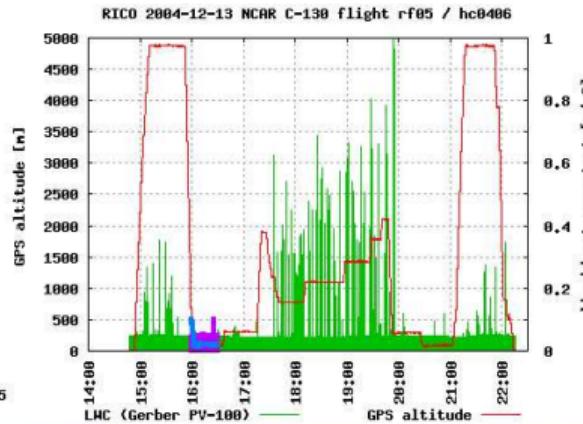
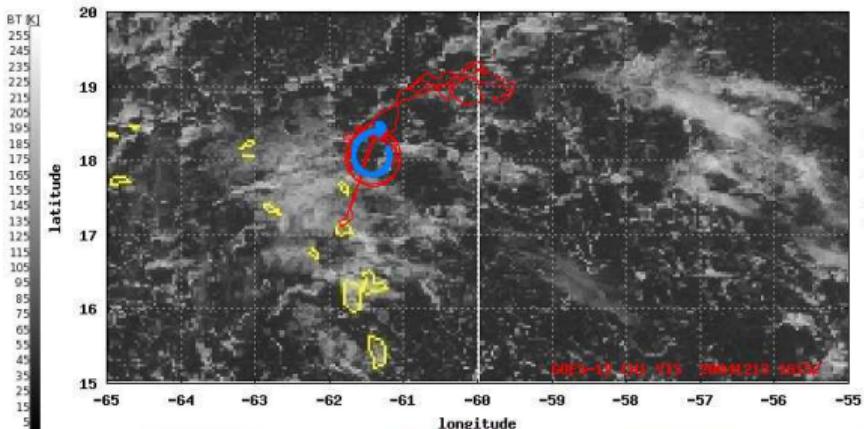
lot badawczy RICO: C-130 RF05



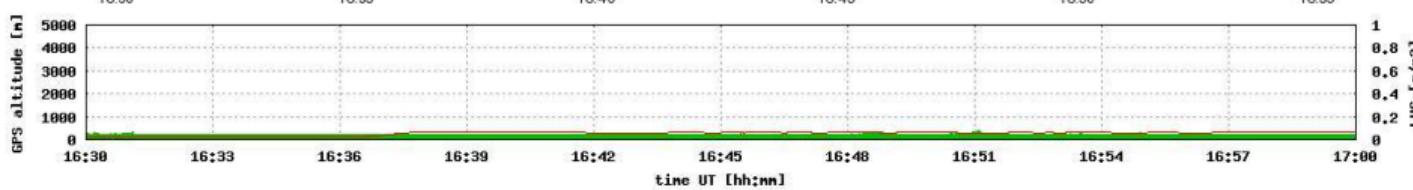
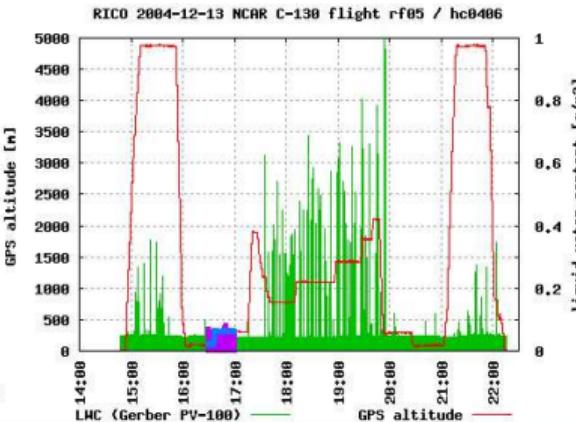
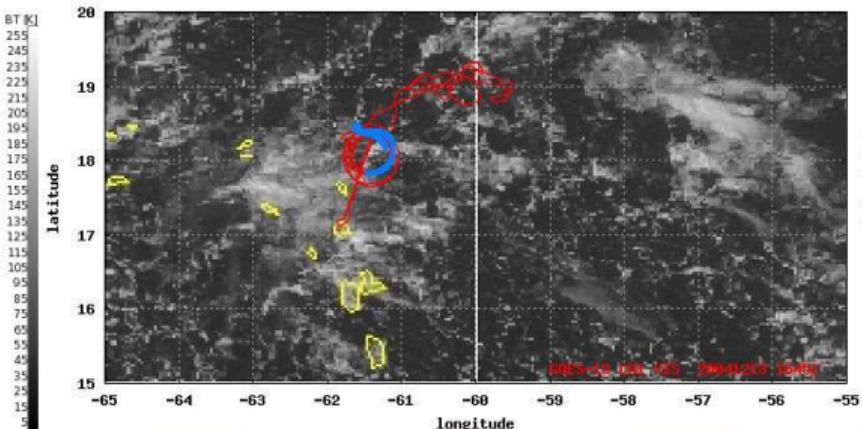
lot badawczy RICO: C-130 RF05



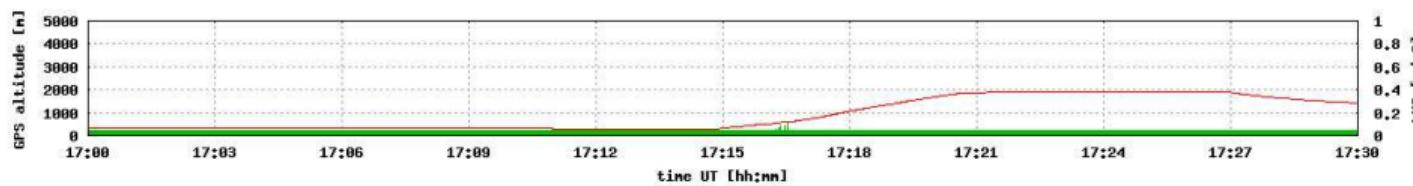
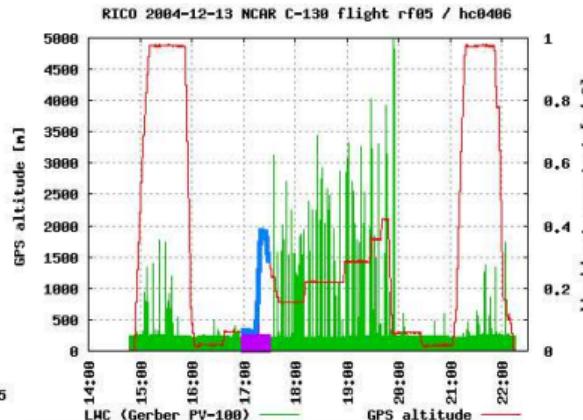
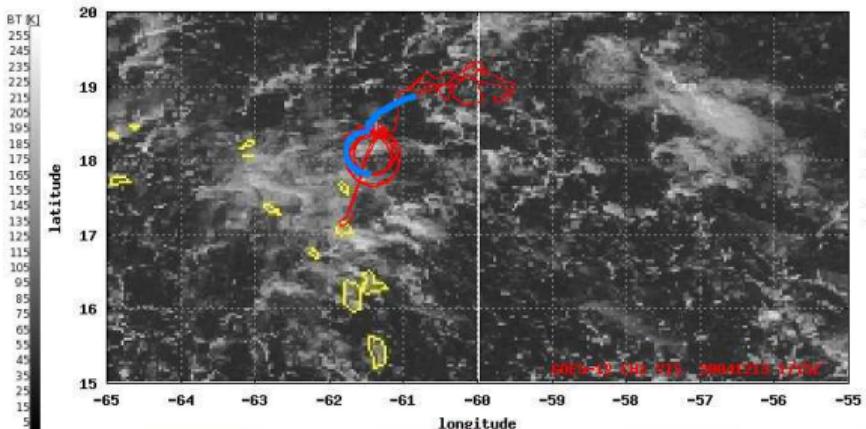
lot badawczy RICO: C-130 RF05



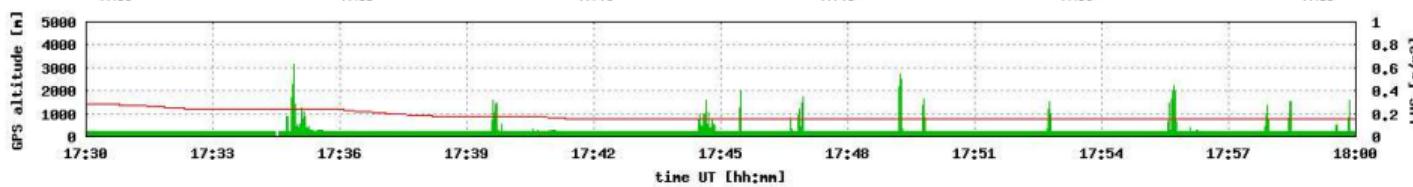
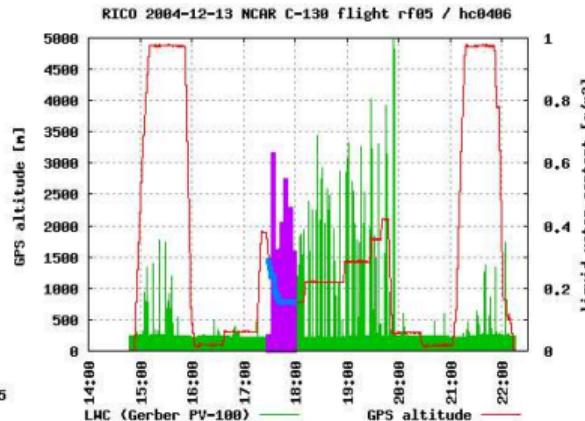
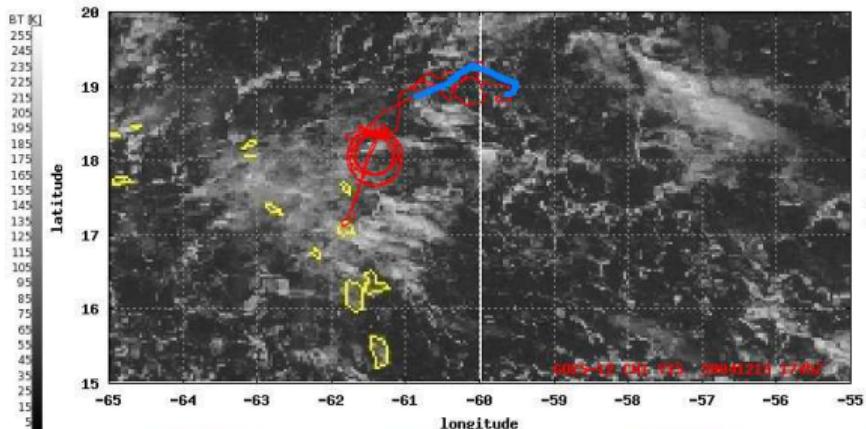
lot badawczy RICO: C-130 RF05



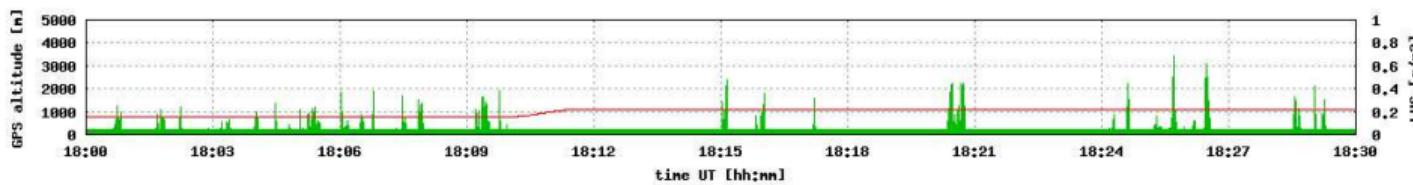
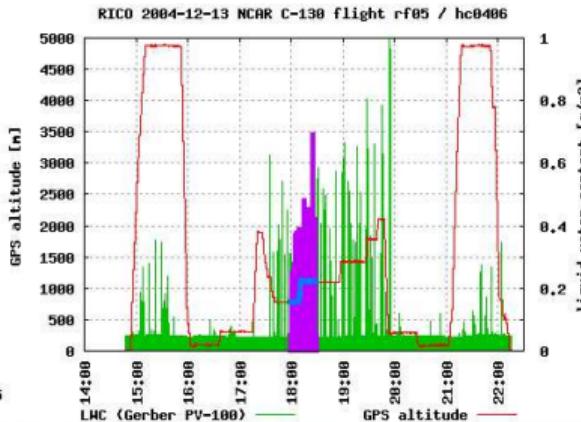
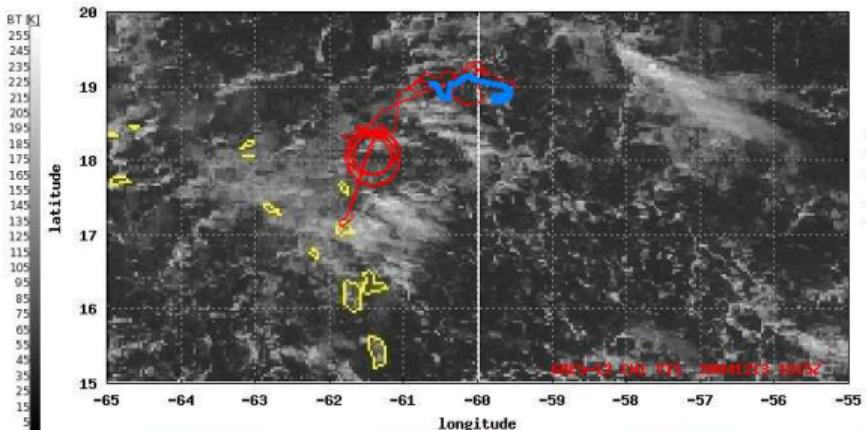
lot badawczy RICO: C-130 RF05



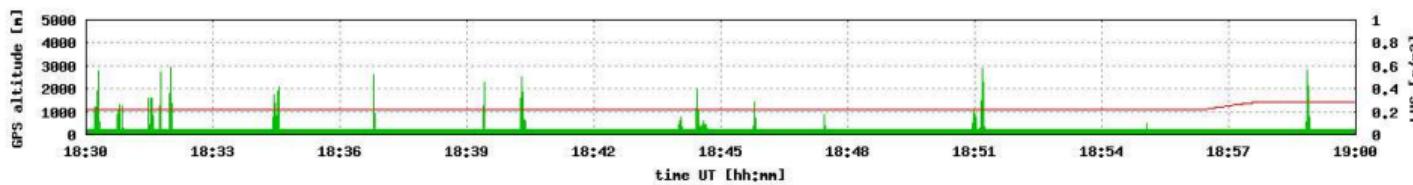
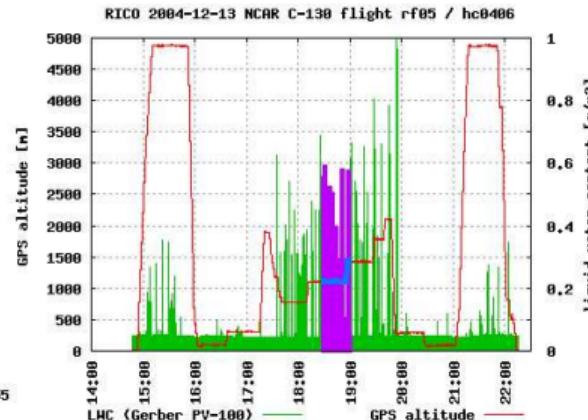
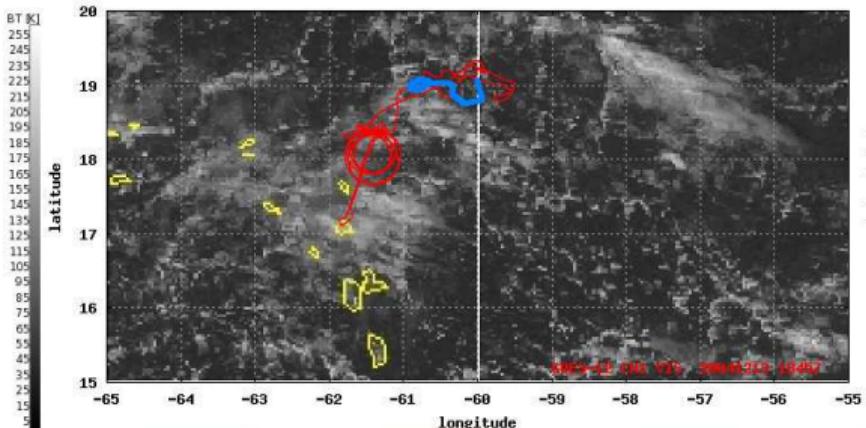
lot badawczy RICO: C-130 RF05



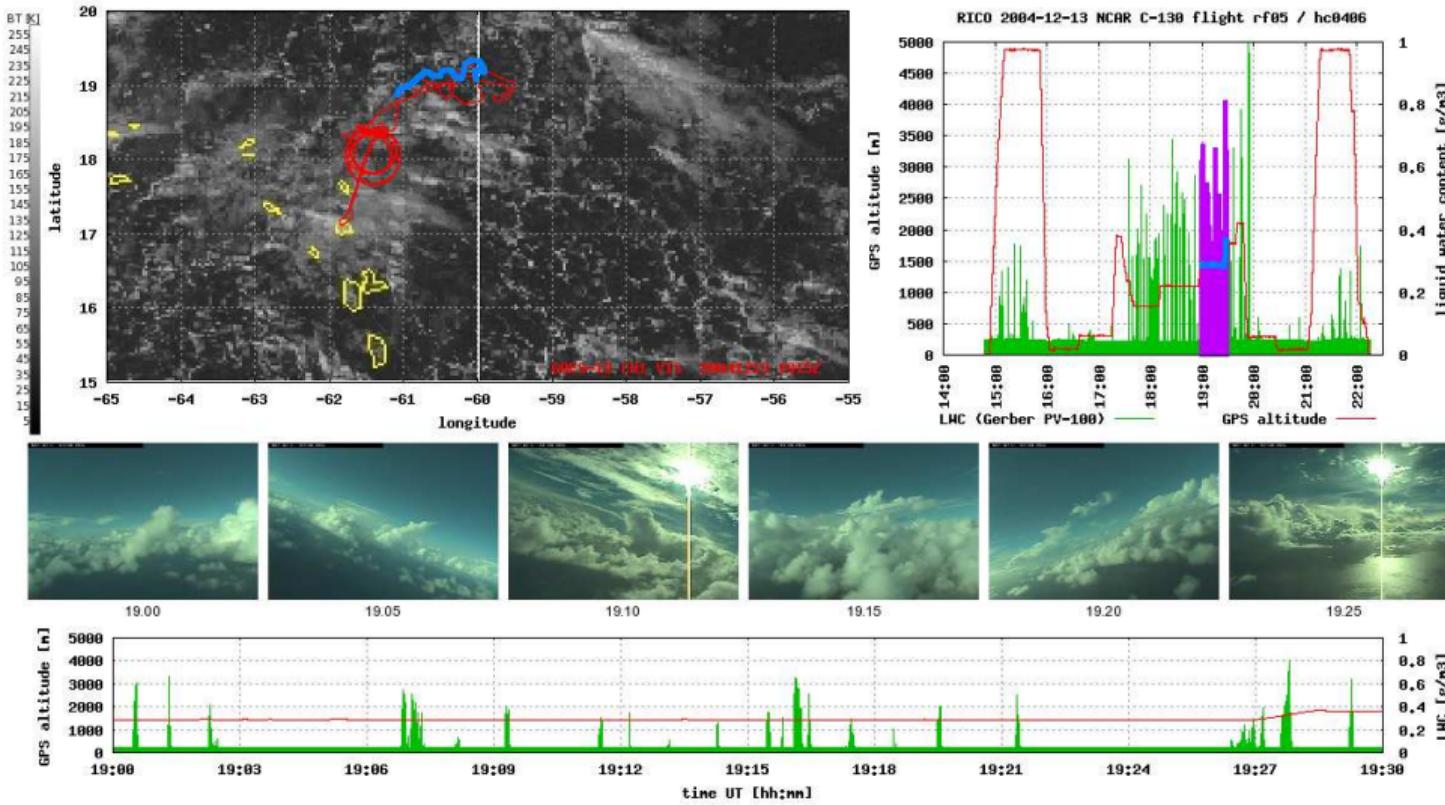
lot badawczy RICO: C-130 RF05



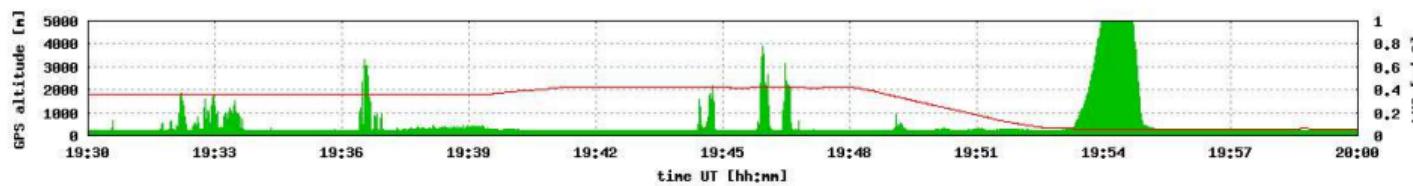
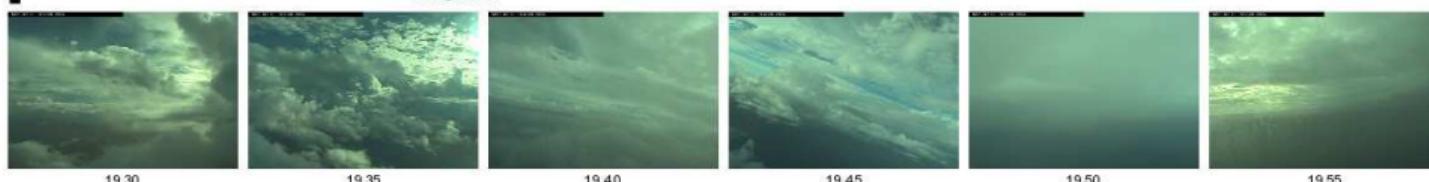
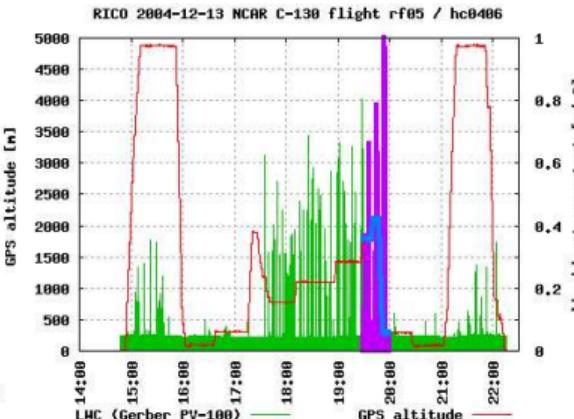
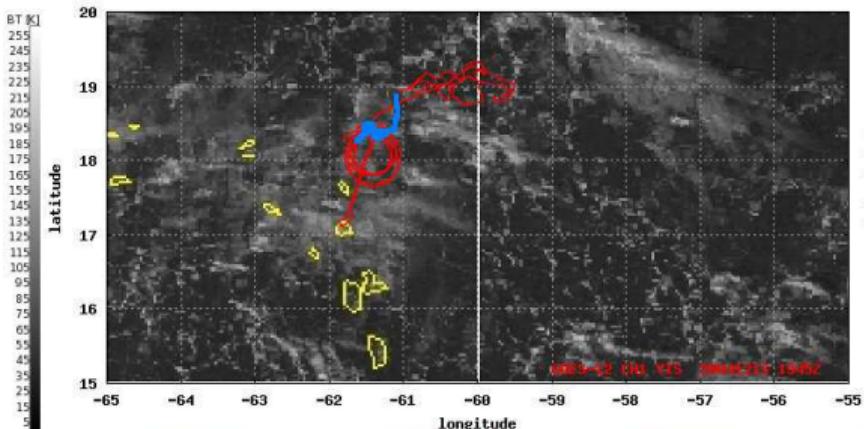
lot badawczy RICO: C-130 RF05



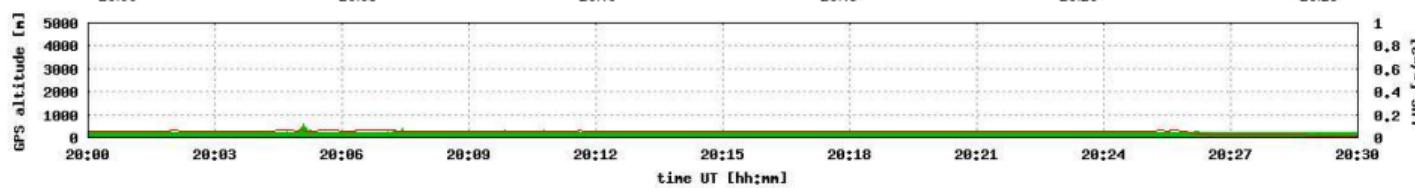
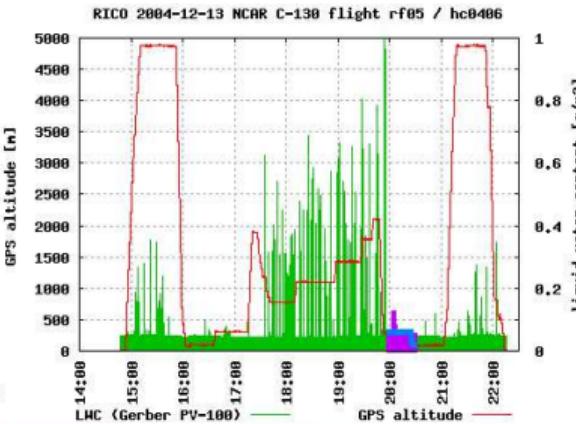
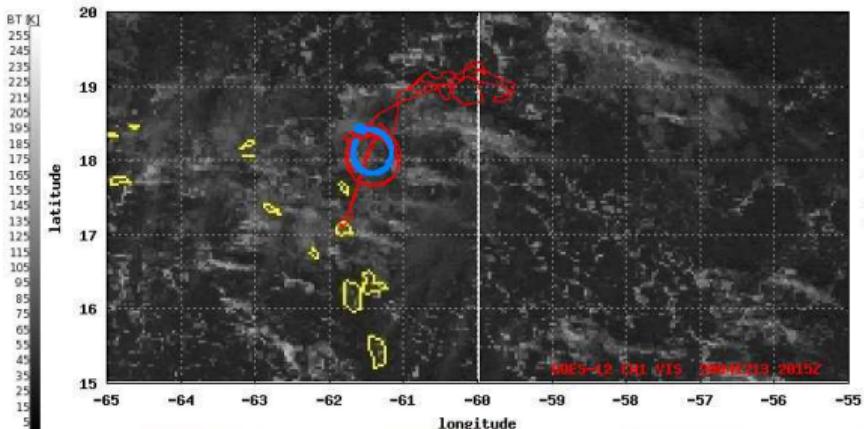
lot badawczy RICO: C-130 RF05



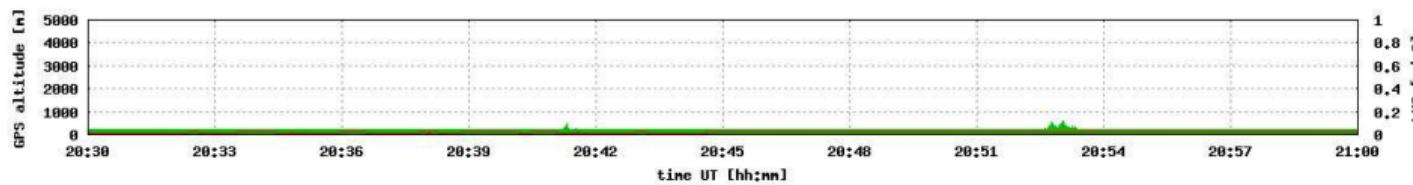
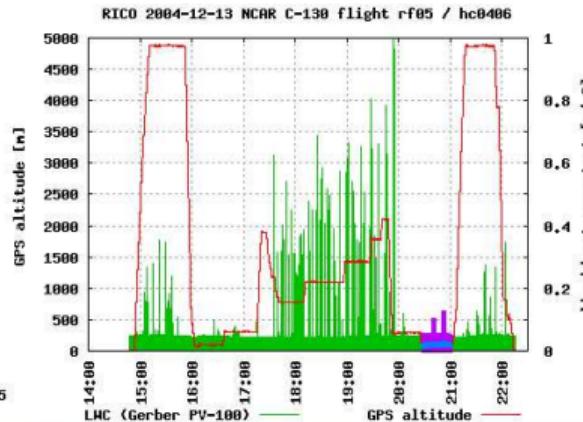
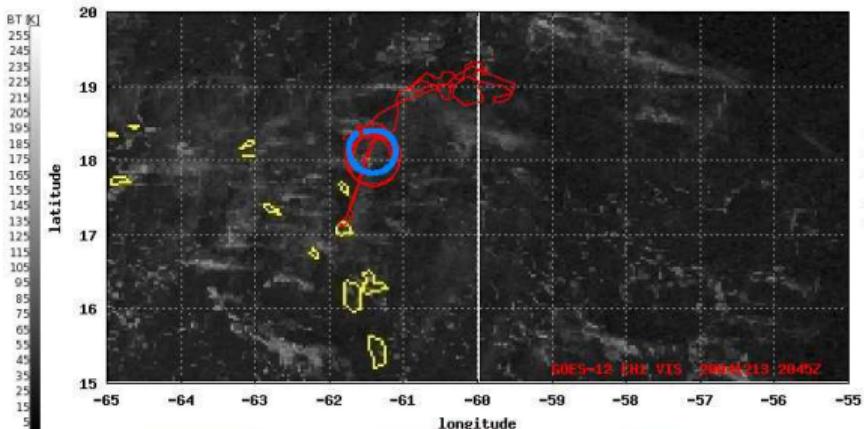
lot badawczy RICO: C-130 RF05



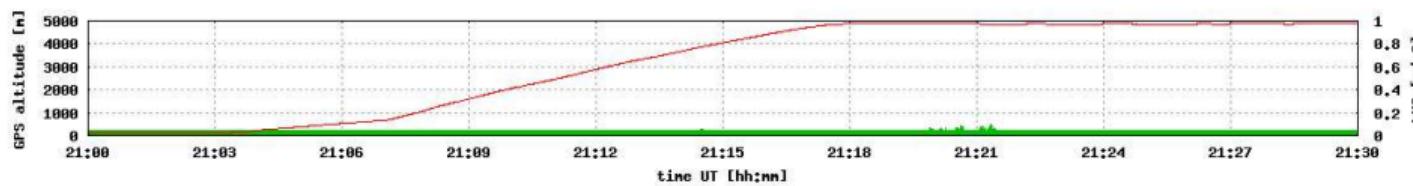
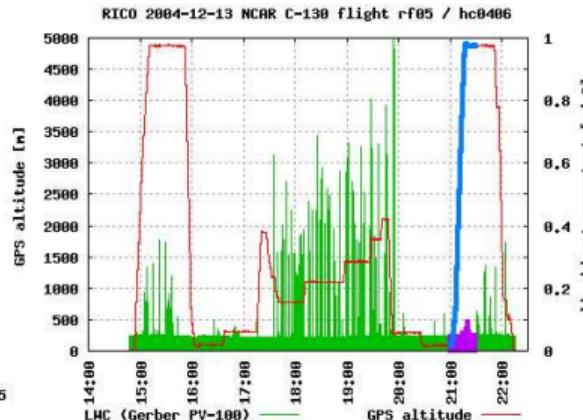
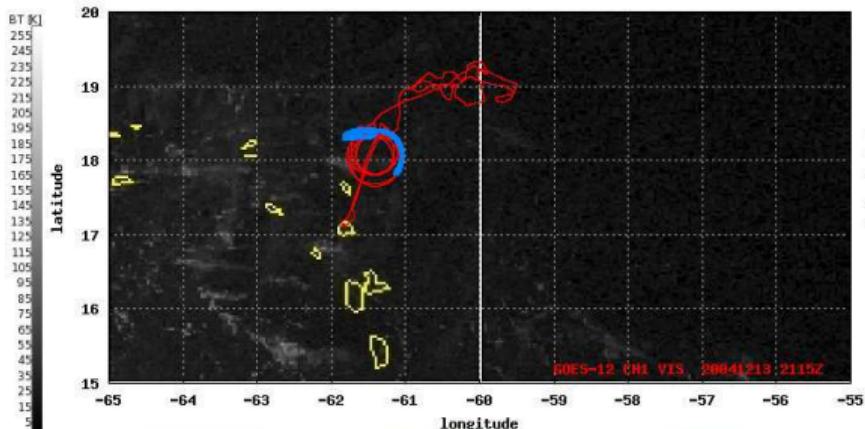
lot badawczy RICO: C-130 RF05



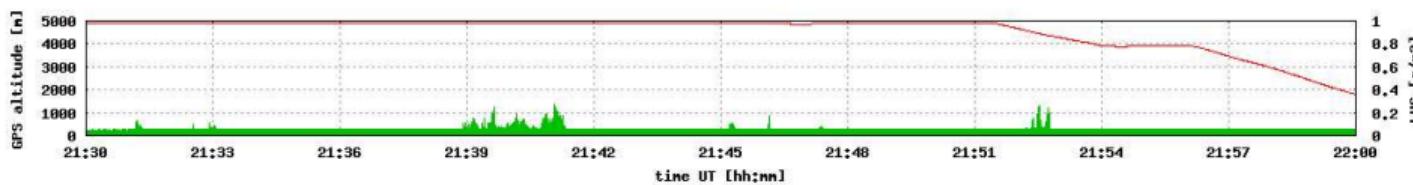
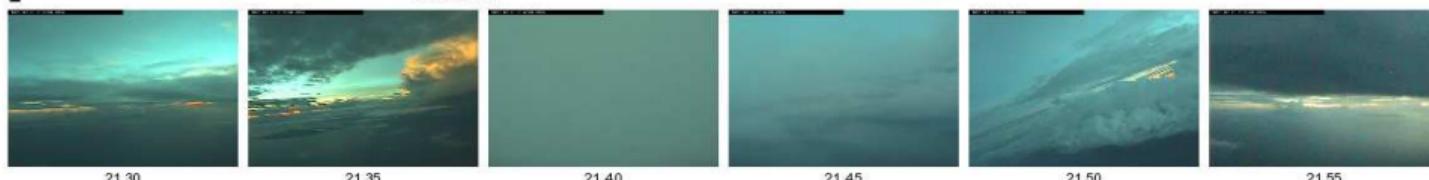
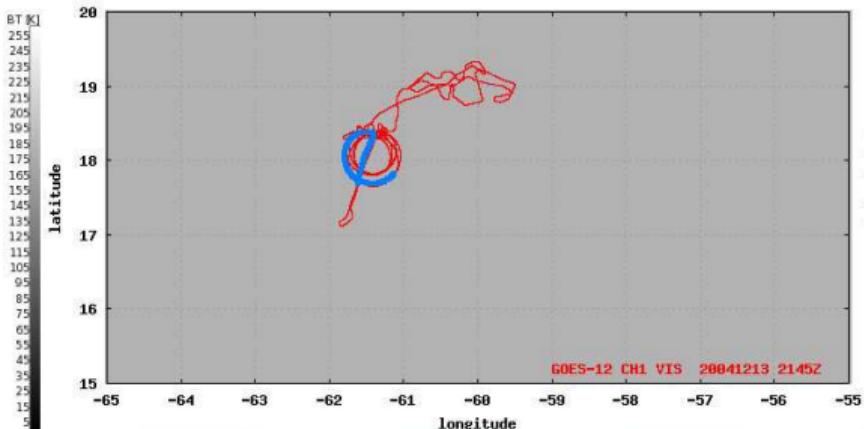
lot badawczy RICO: C-130 RF05



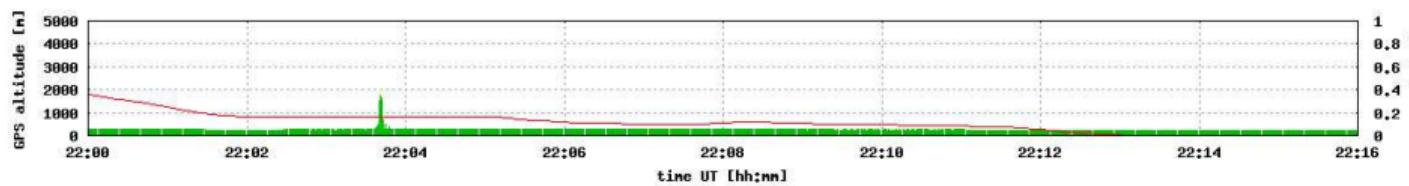
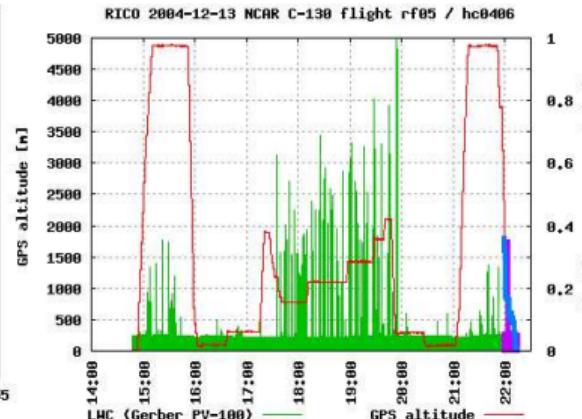
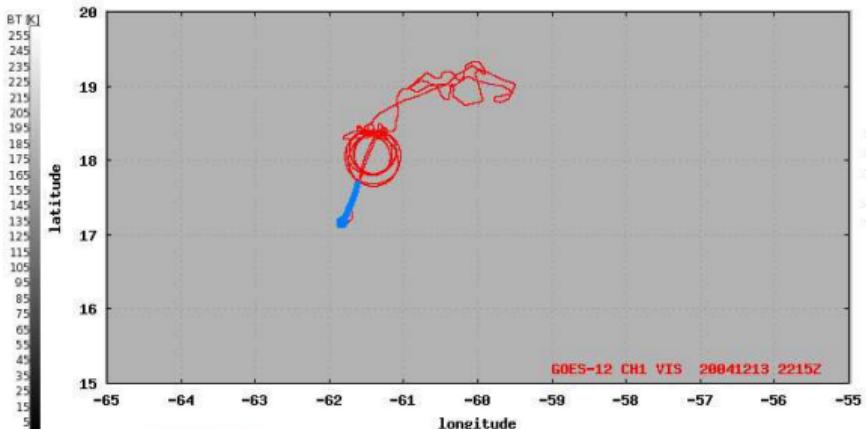
lot badawczy RICO: C-130 RF05



lot badawczy RICO: C-130 RF05

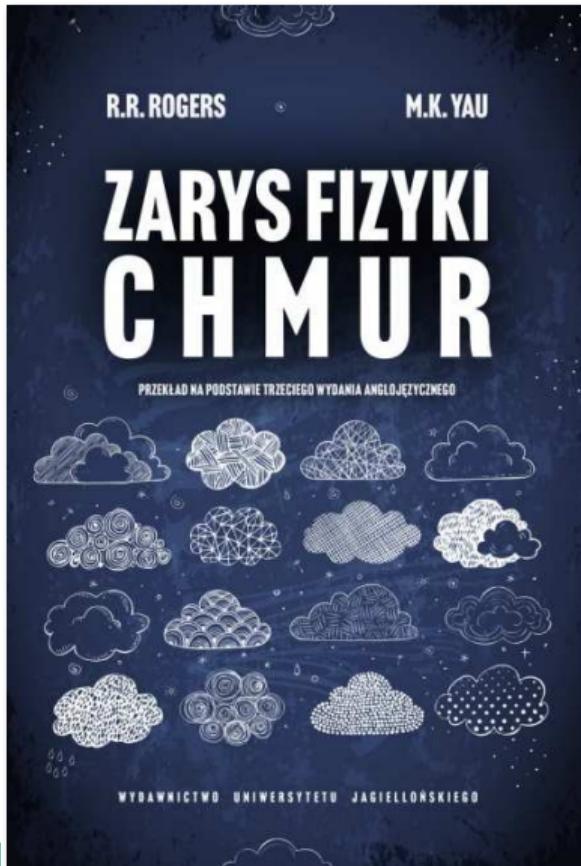


lot badawczy RICO: C-130 RF05



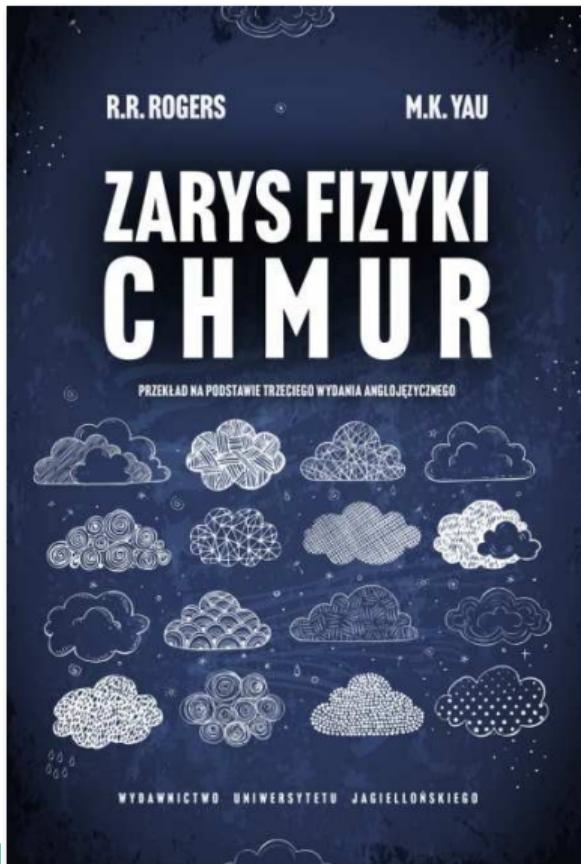
na zakończenie...

wuj.pl/ksiazka/zarys-fizyki-chmur



na zakończenie...

wuj.pl/ksiazka/zarys-fizyki-chmur



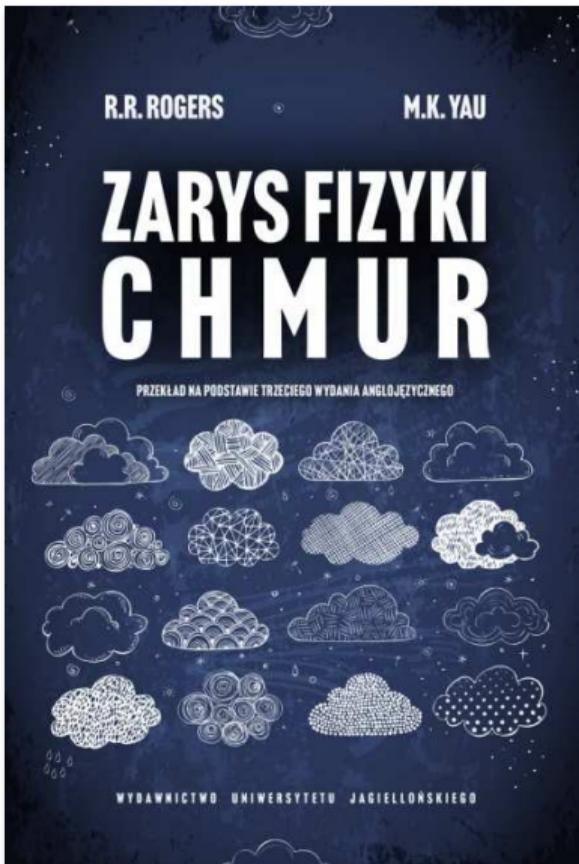
otwarte pakiety (Python, C++) rozwijane w ZFS:
github.com/open-atmos & github.com/numba-mpi

tematy prac dyplomowych (inżynieria oprogramowania
i fizyka chmur): <https://apd.usos.agh.edu.pl/>

zapraszam do współpracy!
(kontakt: sylwester.arabas@agh.edu.pl)

na zakończenie...

wuj.pl/ksiazka/zarys-fizyki-chmur



otwarte pakiety (Python, C++) rozwijane w ZFS:
github.com/open-atmos & github.com/numba-mpi

tematy prac dyplomowych (inżynieria oprogramowania i fizyka chmur): <https://apd.usos.agh.edu.pl/>

zapraszam do współpracy!
(kontakt: sylwester.arabas@agh.edu.pl)

więcej o bifurkacjach (i katastrofach) w chmurach:
Arabas & Shima 2017 (doi:10.5194/npg-24-535-2017)
dziękuję za uwagę!