

# 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

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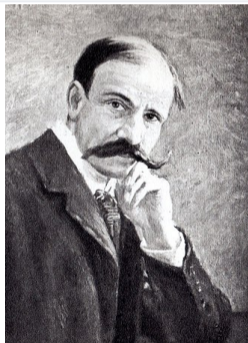
**Maurycy Pius Rudzki** (b. 1862, d. 1916) was the first person to call himself a professor of geophysics. He held the Chair of Geophysics at the Jagiellonian University in Kraków, and established the Institute of Geophysics there in 1895. His research specialty was elastic anisotropy, as applied to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

### References

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

**Maurycy Pius Rudzki**



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

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*Kontrast między rozmiarami kropeł deszczowych, z których składają się chmury, a rozmiarami kropeł deszczowych, jest tak wielki, że te ostatnie oczywiście nie mogą pochodzić wprost z kondensacyi, tylko z łączenia się wielu małych kropelek...*

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



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



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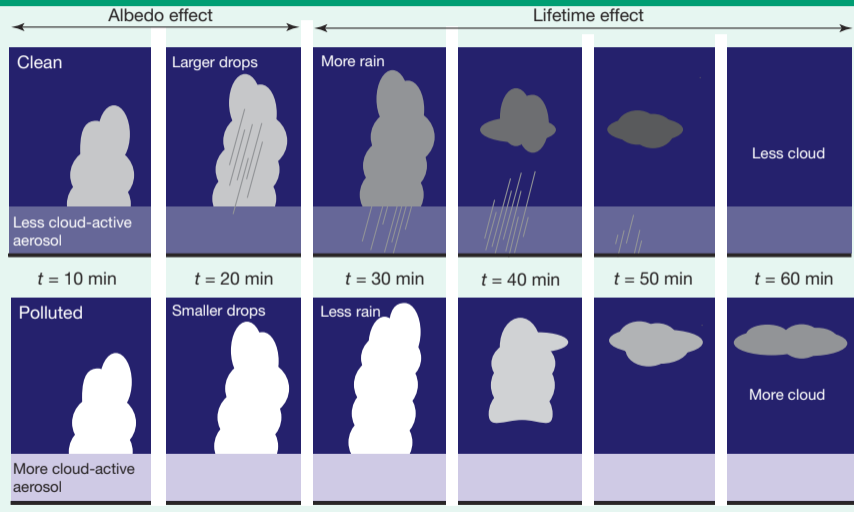


no particles  $\rightsquigarrow$  no clouds

<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”*

# modelowanie chmur (w systemie Ziemi): skale przestrzenne (i czasowe)



“Cloud and ship. Ukraine, Crimea, Black sea, view from Ai-Petri mountain”

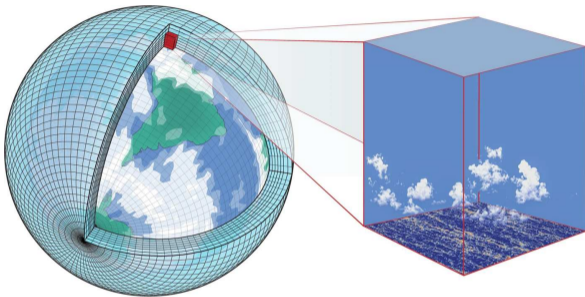
(photo: Yevgen Timashov / National Geographic)

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“Cloud and ship. Ukraine, Crimea, Black sea, view from Ai-Petri mountain”

(photo: Yevgen Timashov / National Geographic)



“Grid cells in a global climate model and a large-eddy simulation of shallow cumulus clouds at 5 m resolution”

(fig. from Schneider et al. 2017)

# modelowanie chmur (w systemie Ziemi): niepewności



The screenshot shows the IPCC website homepage. At the top, there is a blue navigation bar with a menu icon and the word 'MENU'. To the right of the menu are links for 'ABOUT', 'DATA', 'DOCUMENTATION', 'FOCAL POINTS PORTAL', 'BUREAU PORTAL', 'LIBRARY', 'LINKS', 'LANGUAGES', and a search icon with the text 'SEARCH'. Below the navigation bar is the IPCC logo and a secondary navigation menu with links for 'REPORTS', 'SYNTHESIS REPORT', 'WORKING GROUPS', 'ACTIVITIES', 'NEWS', and 'CALENDAR'. On the right side of this menu are 'FOLLOW' and 'SHARE' icons. The main content area features a large title 'The Intergovernmental Panel on Climate Change' and a descriptive paragraph: 'The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change.' At the bottom, there is a grey box containing the text 'WORKING GROUP II SIXTH ASSESSMENT REPORT' and three logos: WHO, UNEP, and the Nobel Peace Prize logo.

MENU

ABOUT DATA DOCUMENTATION FOCAL POINTS PORTAL BUREAU PORTAL LIBRARY LINKS LANGUAGES SEARCH

ipcc

REPORTS SYNTHESIS REPORT WORKING GROUPS ACTIVITIES NEWS

CALENDAR

FOLLOW SHARE

## The Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change.

WORKING GROUP II SIXTH ASSESSMENT REPORT

WHO UNEP Nobel PEACE PRIZE OF THE NOBEL FOUNDATION

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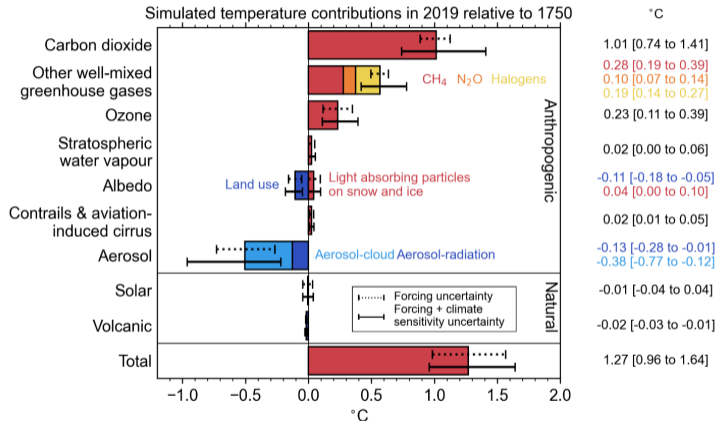


Figure 7.7: The contribution of forcing agents to 2019 temperature change relative to 1750 produced using the two-layer emulator (Supplementary Material 7.SM.2), constrained to assessed ranges for key climate metrics described in Cross-Chapter Box 7.1.



# modelowanie chmur: opis widma aerozolu i hydrometeorów

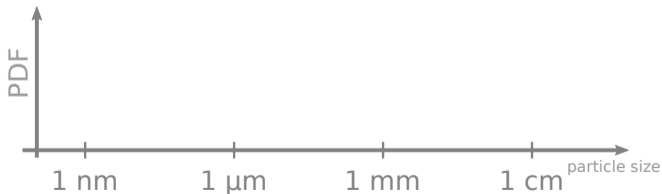
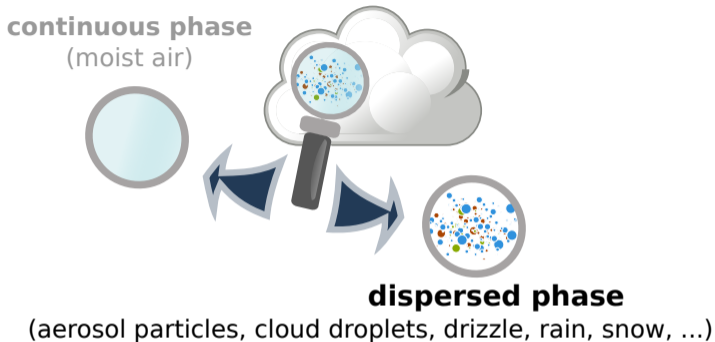
**continuous phase**  
(moist air)



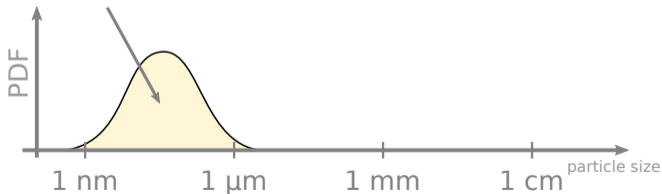
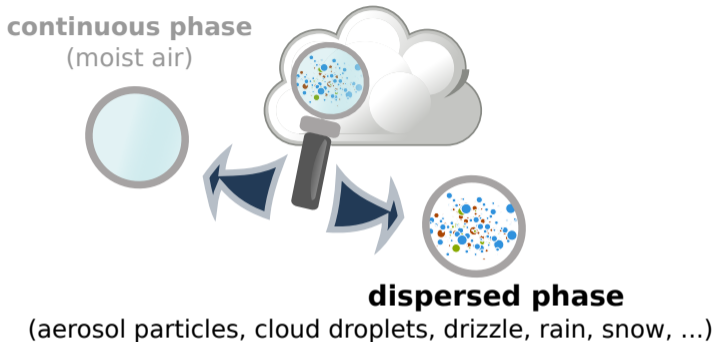
**dispersed phase**

(aerosol particles, cloud droplets, drizzle, rain, snow, ...)

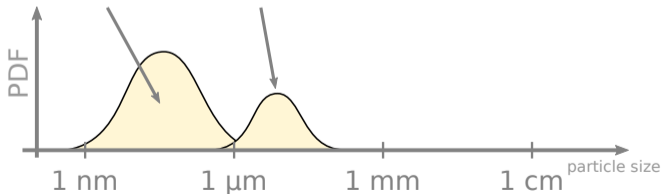
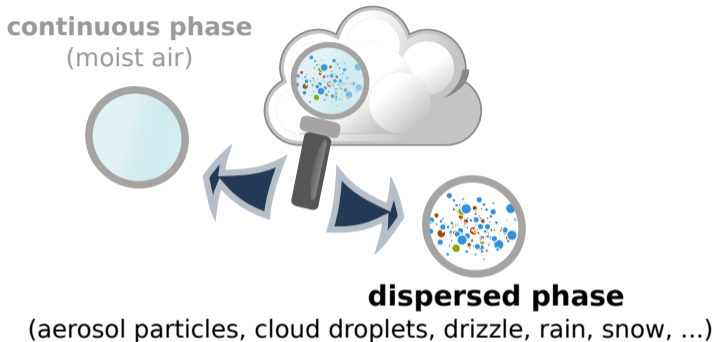
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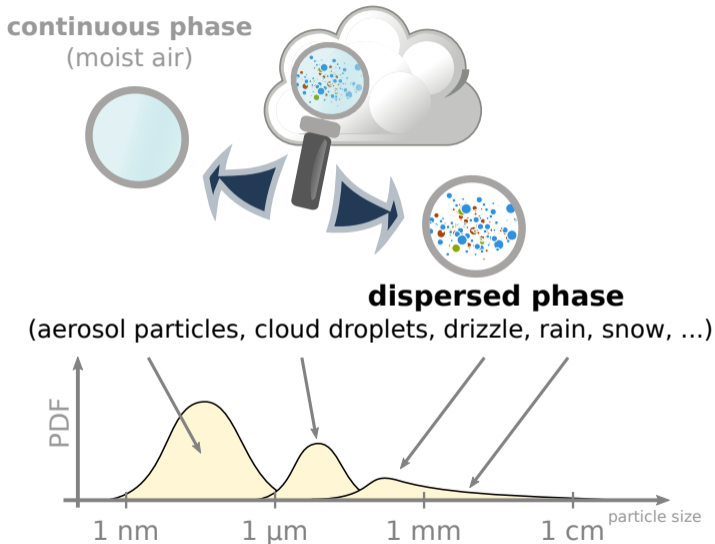
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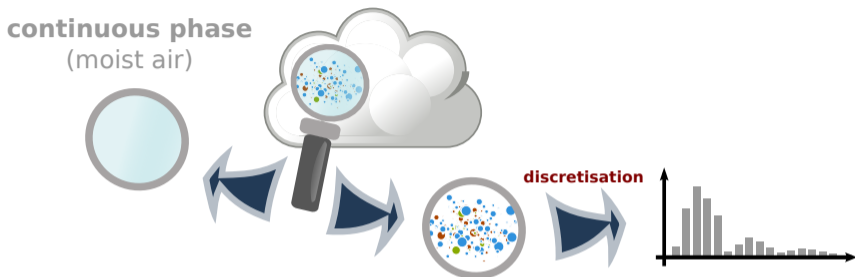
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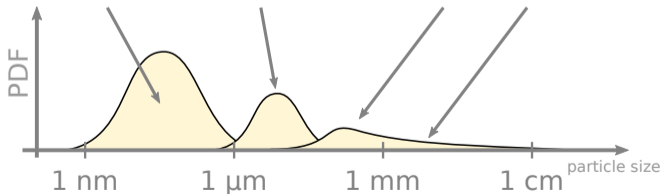
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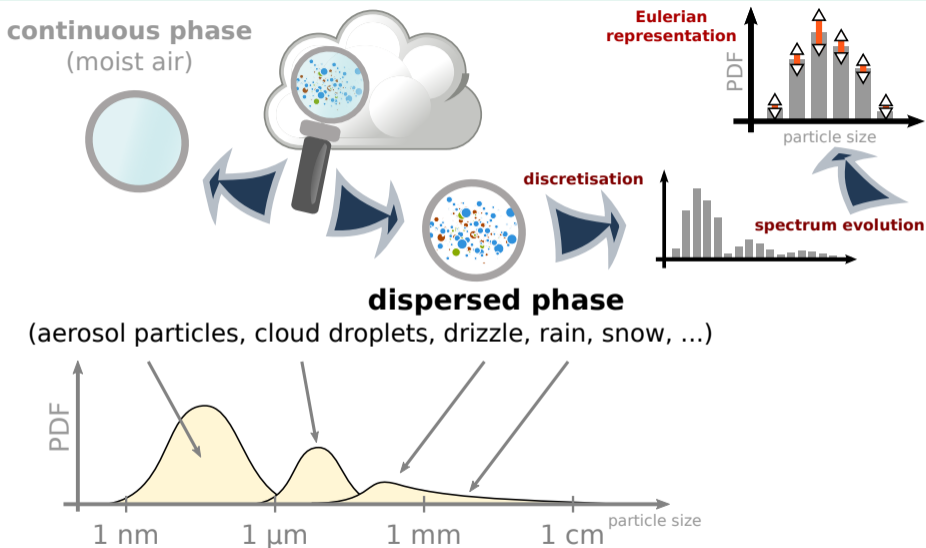
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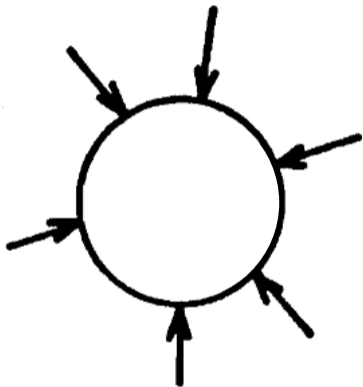


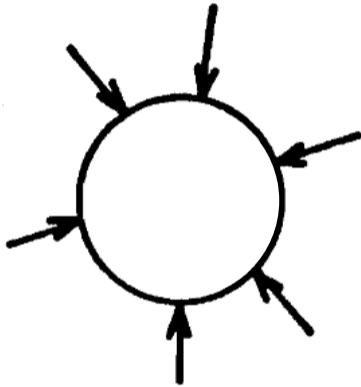
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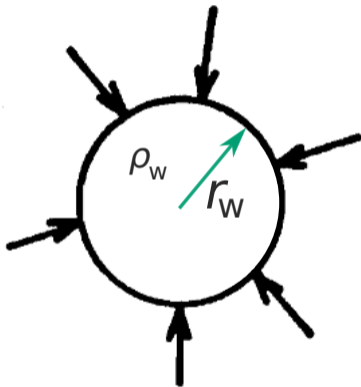


prawa Ficka i Fouriera

geometria sferyczna

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

# opis kondensacji i parowania kropli: dyfuzja masy i ciepła

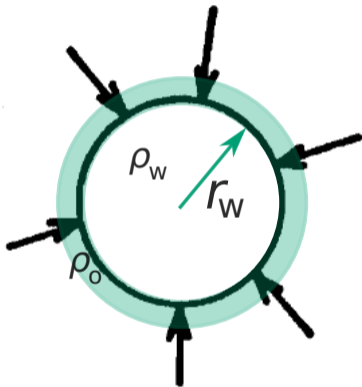


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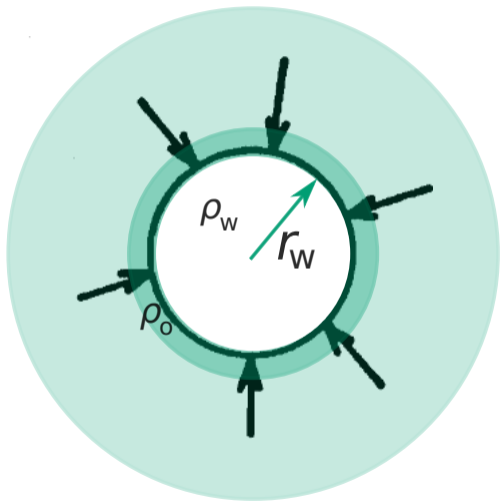


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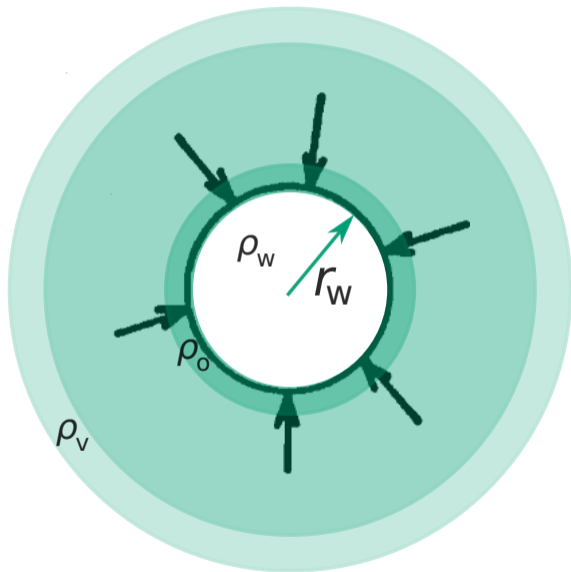


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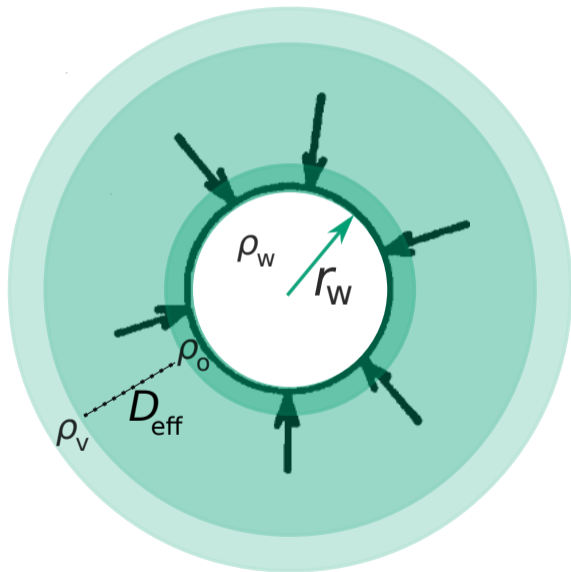


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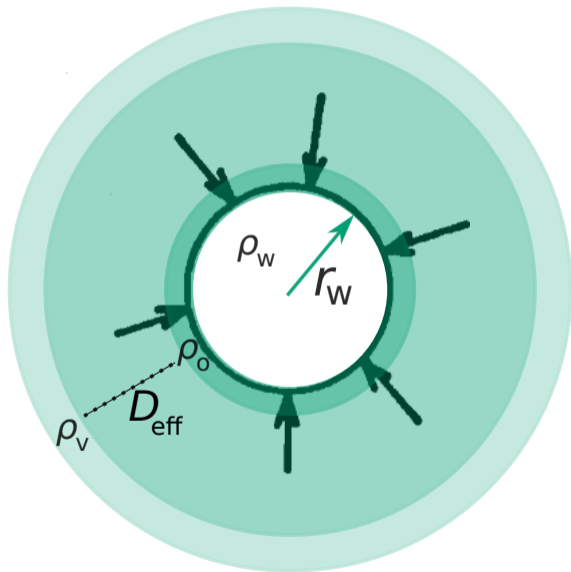


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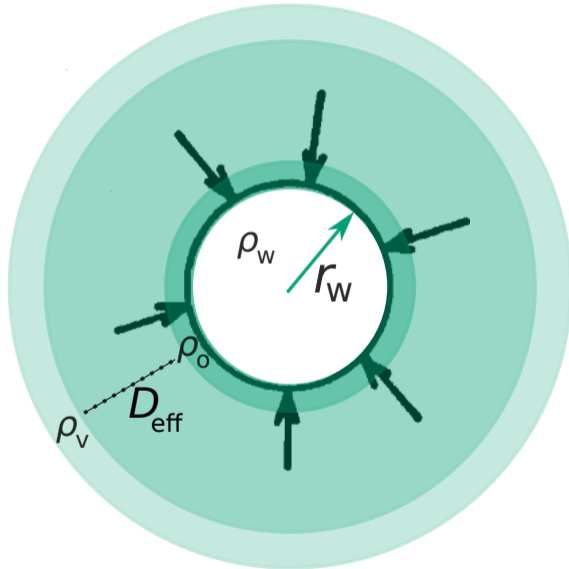
$$\dot{r}_w = \frac{1}{r_w} \frac{D_{eff}}{\rho_w} (\rho_v - \rho_o)$$

liczby bezwymiarowe:

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$$RH_{eq} = \rho_o / \rho_{vs}$$

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geometria sferyczna

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## opis kondensacji i parowania kropli: krzywa Köhlera

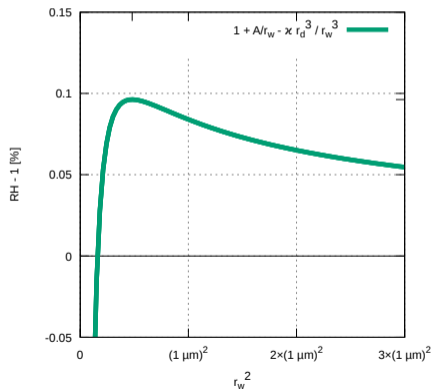
$$\dot{r}_w = \frac{1}{r_w} D_{\text{eff}} \frac{\rho_{vs}}{\rho_w} (\text{RH} - \text{RH}_{\text{eq}})$$

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

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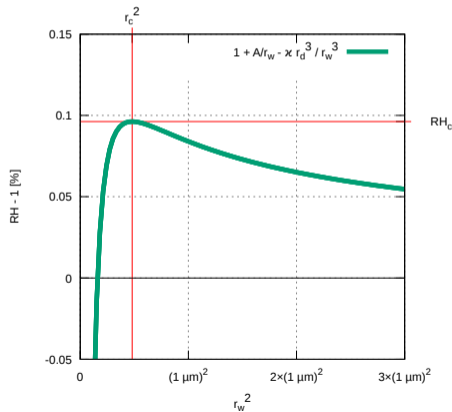


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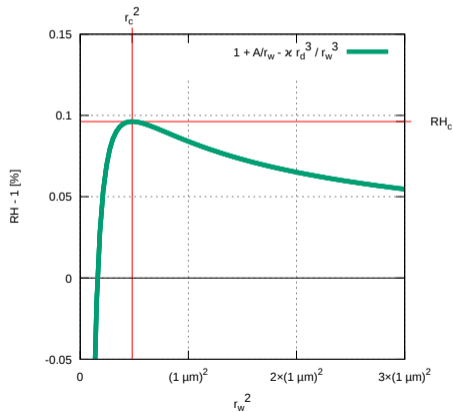
$$\approx 1 + \frac{A}{r_w} - \frac{\kappa r_d^3}{r_w^3}$$



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$$\approx 1 + \frac{A}{r_w} - \frac{\kappa r_d^3}{r_w^3}$$



maximum at  $(r_c, \text{RH}_c)$ :

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

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

## oddziaływania aerozol – chmury – opad: zjawiska



- ❑ aktywacja kropelek na aerozolu
- ❑ kondensacja

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- ❑ kondensacja



- ❑ zderzenia pomiędzy kroplkami
- ❑ procesy chemiczne zachodzące w kroplkach



## oddziaływania aerozol – chmury – opad: zjawiska



- ❑ aktywacja kropelek na aerozolu
- ❑ kondensacja

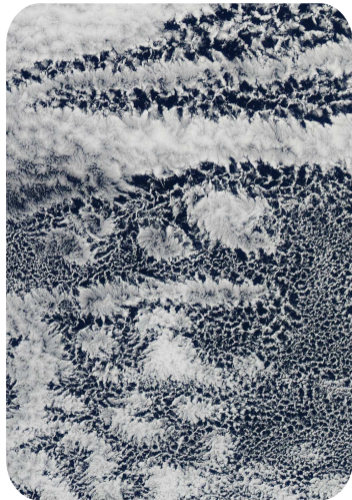
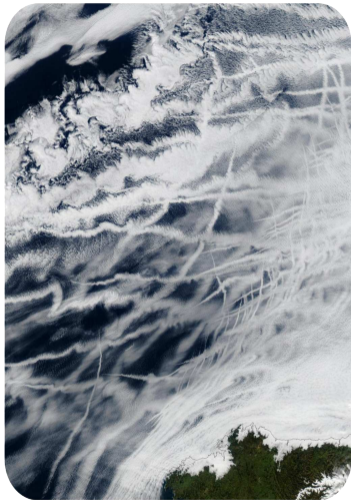


- ❑ zderzenia pomiędzy kropelkami
- ❑ procesy chemiczne zachodzące w kropelkach



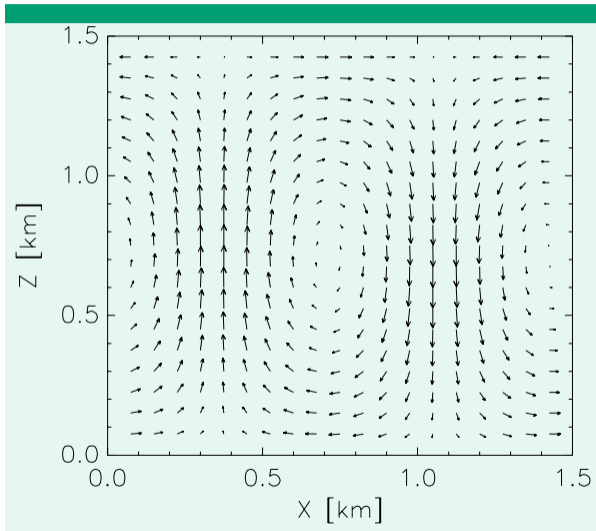
- ❑ opad
- ❑ wmywanie aerozolu
- ❑ odparowywanie kropelek

# oddziaływania aerozol – chmury – aerozol: przykłady

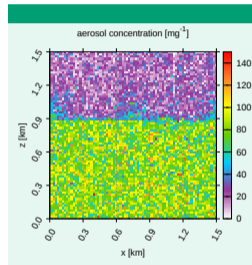
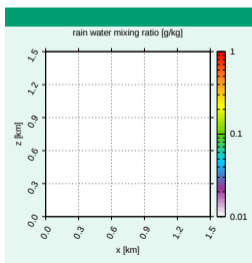
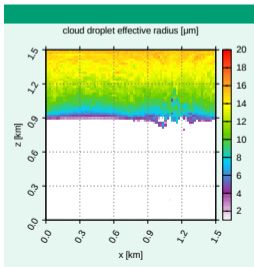
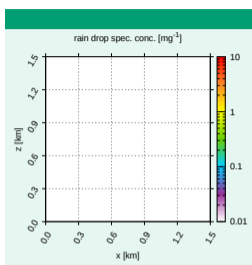
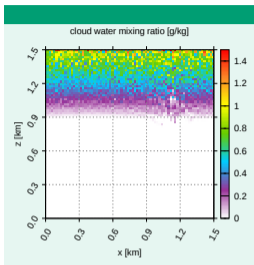


źródło: NASA (27 I 2003 – Zatoka Biskajska; 17 IV 2010 – Pacyfik u wybrzeży Peru)

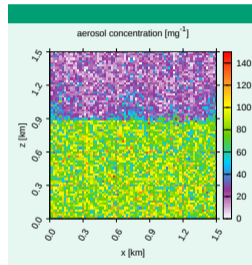
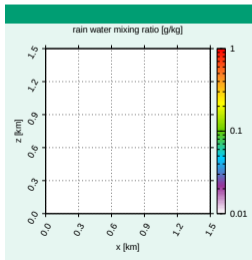
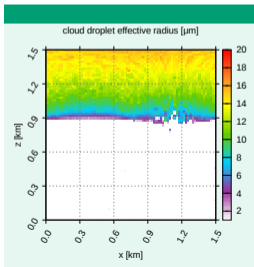
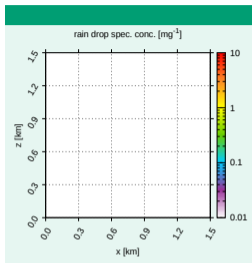
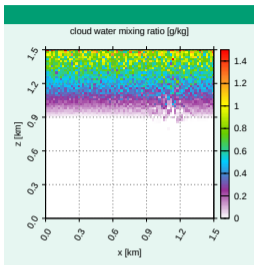
# przykładowa symulacja chmury (2D)



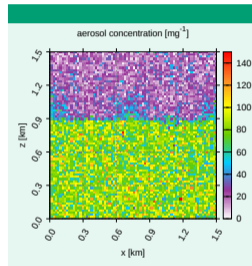
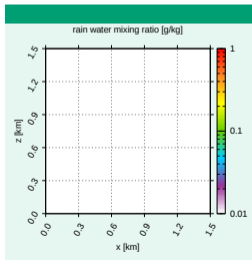
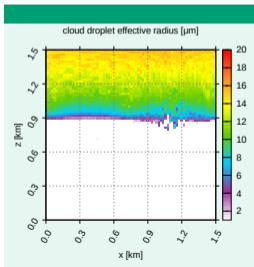
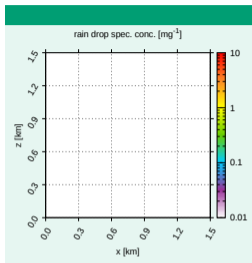
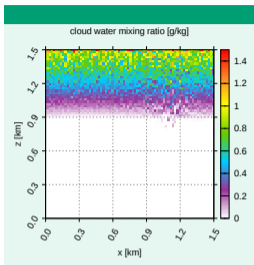
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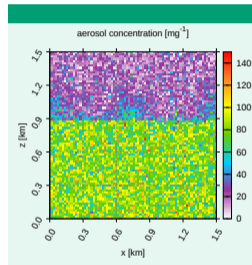
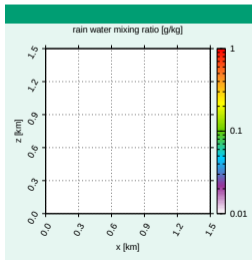
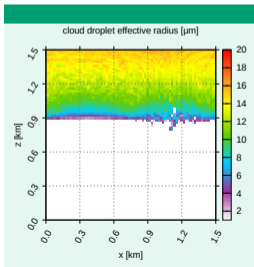
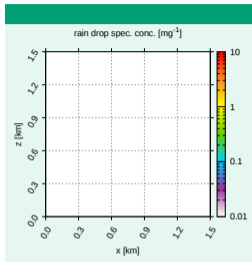
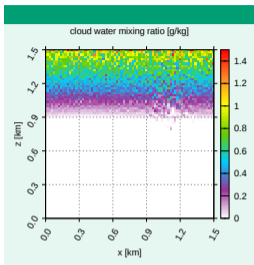
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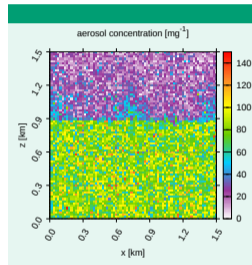
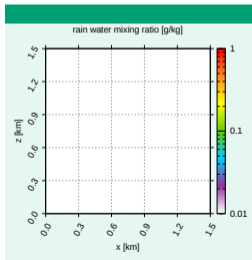
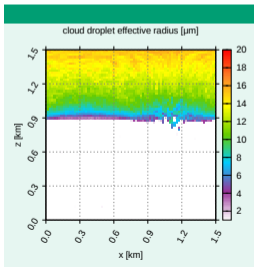
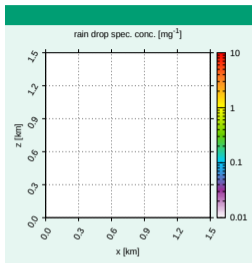
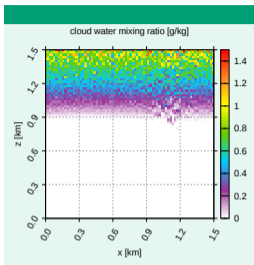
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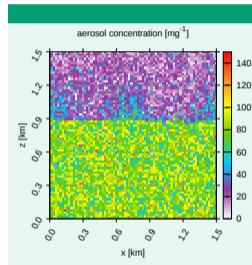
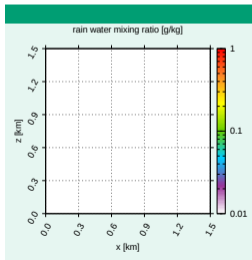
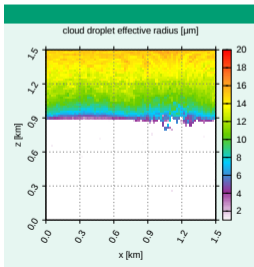
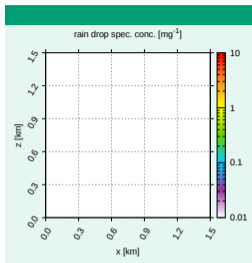
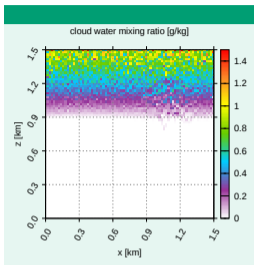
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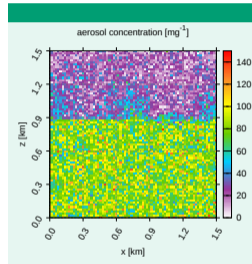
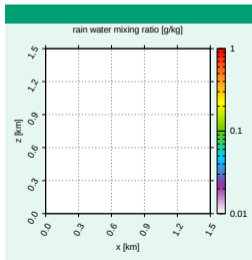
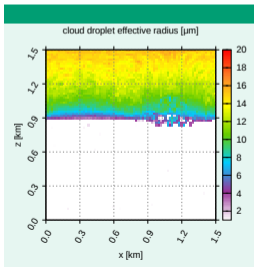
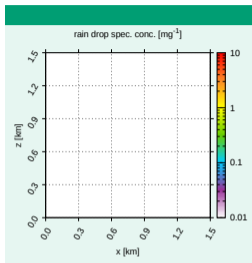
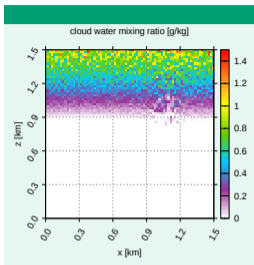
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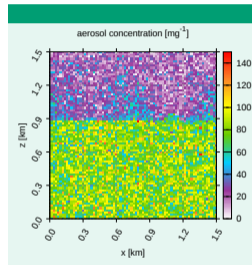
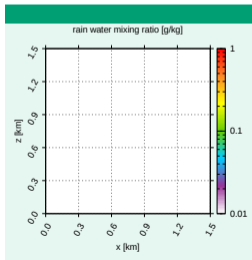
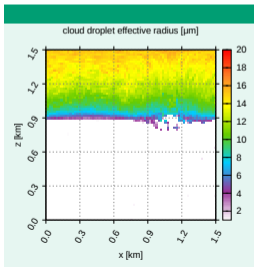
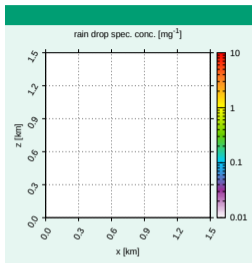
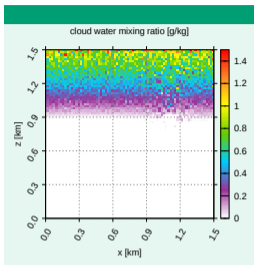
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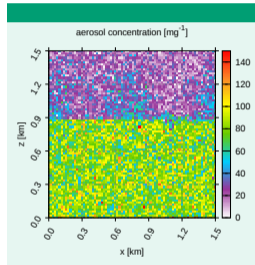
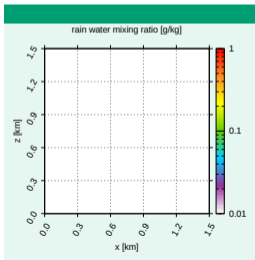
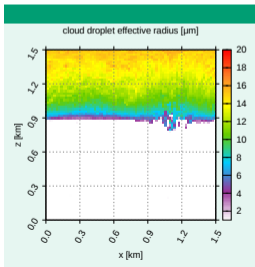
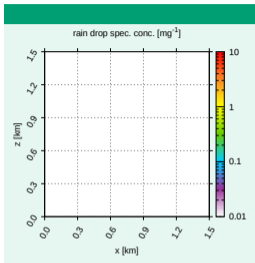
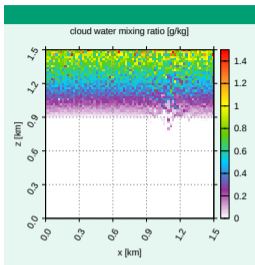
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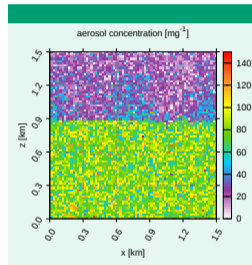
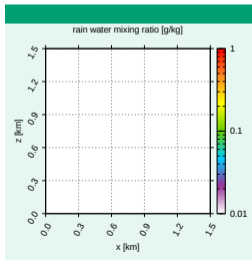
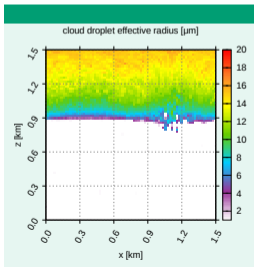
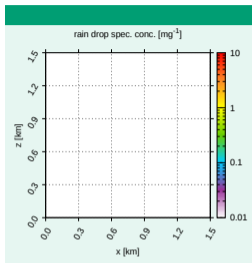
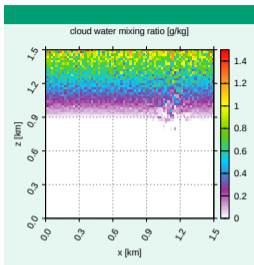
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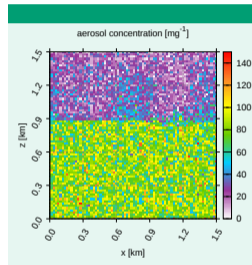
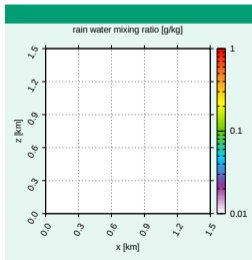
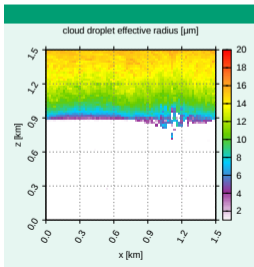
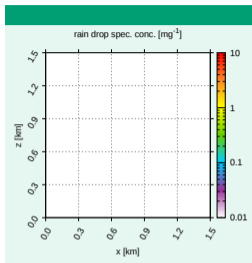
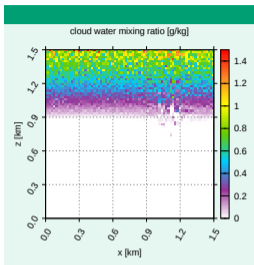
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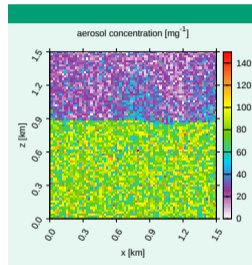
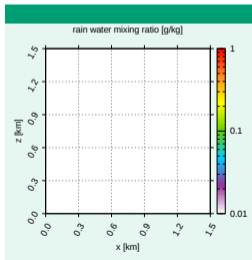
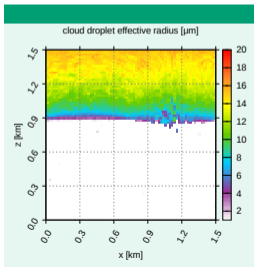
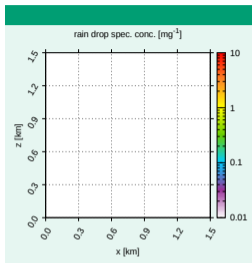
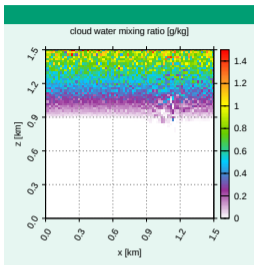
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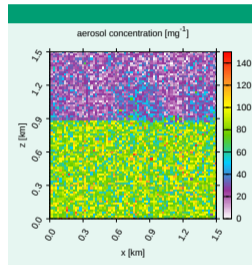
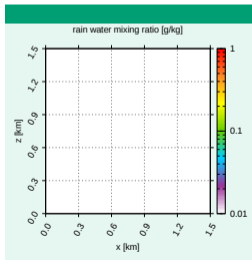
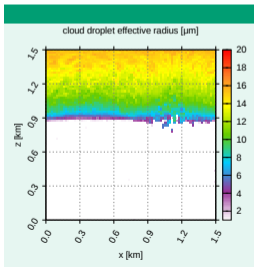
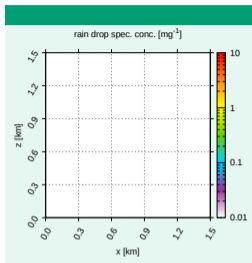
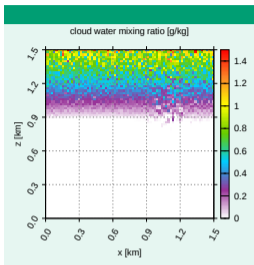
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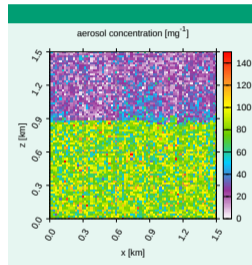
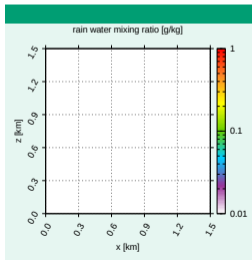
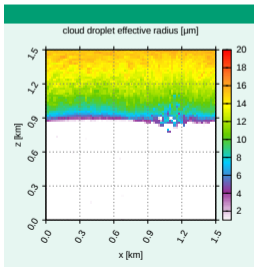
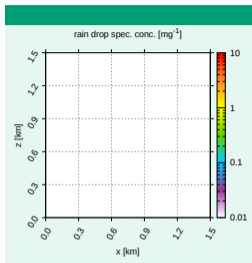
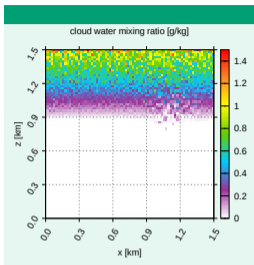
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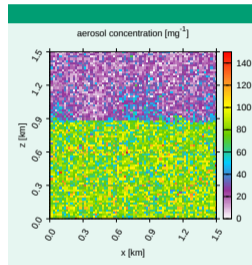
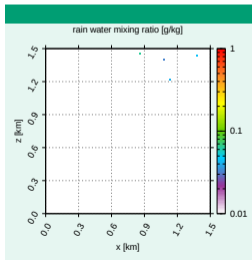
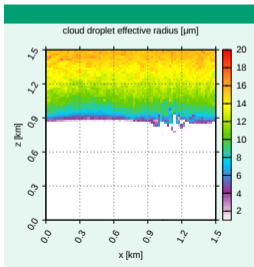
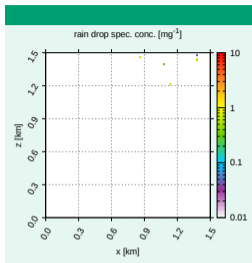
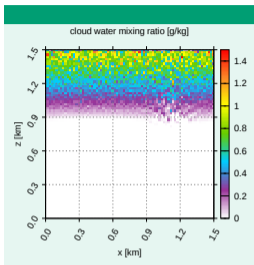
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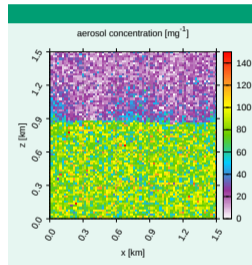
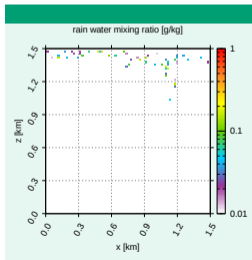
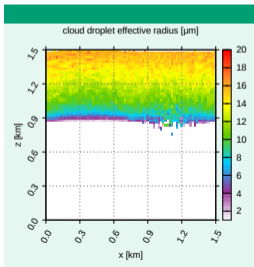
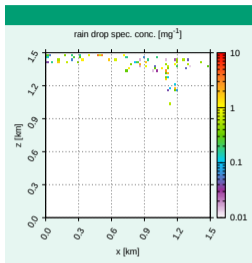
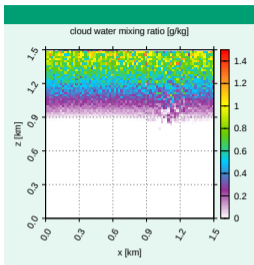
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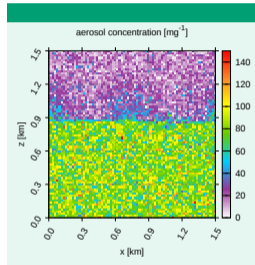
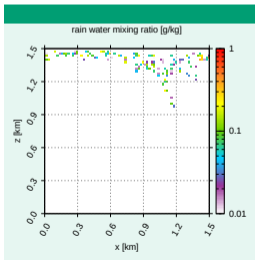
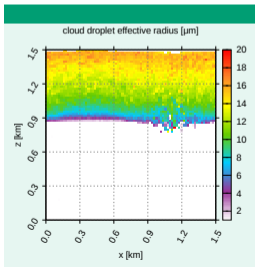
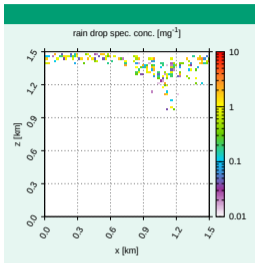
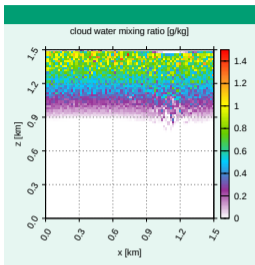
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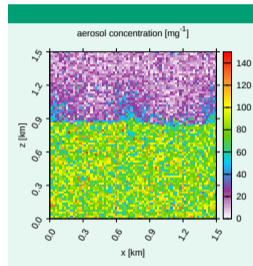
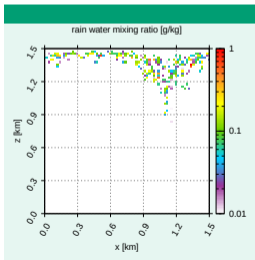
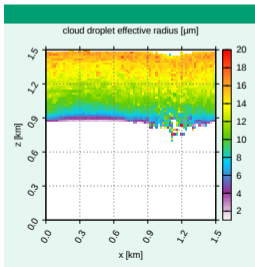
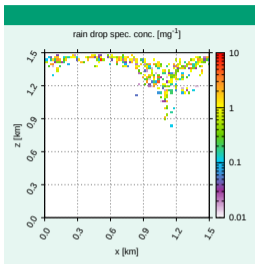
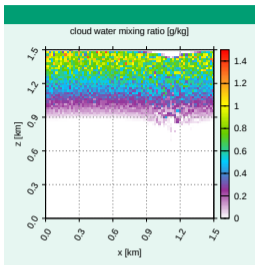
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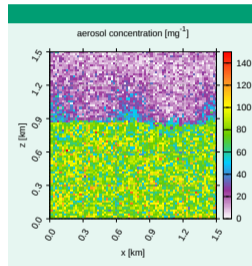
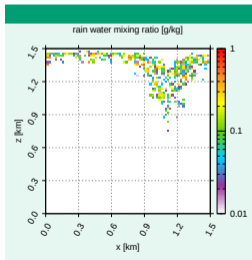
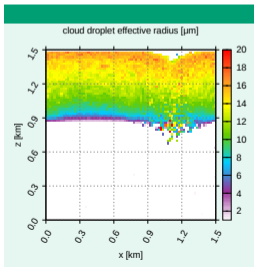
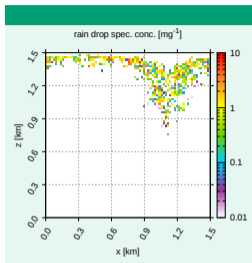
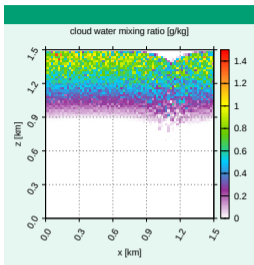
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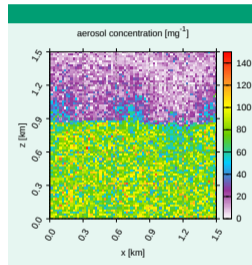
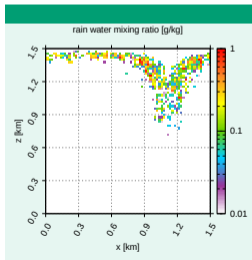
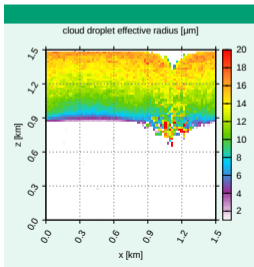
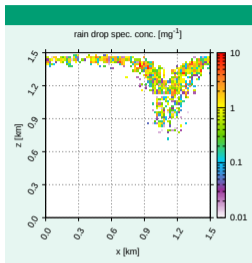
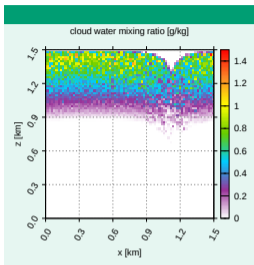
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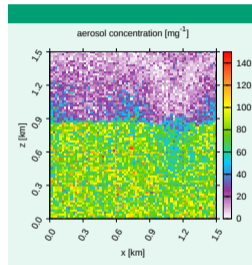
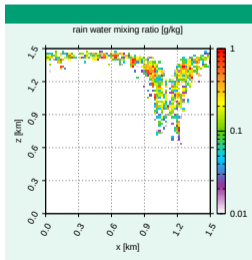
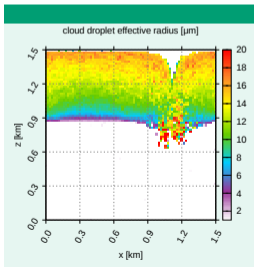
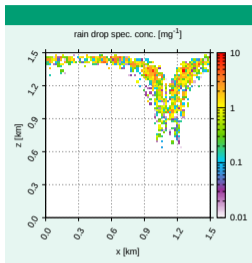
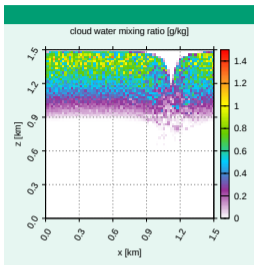
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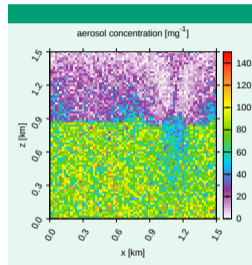
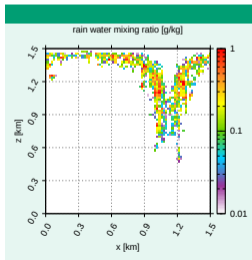
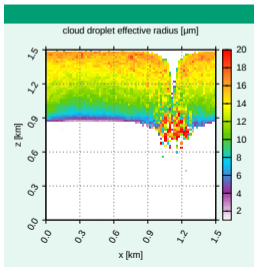
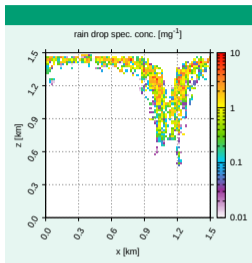
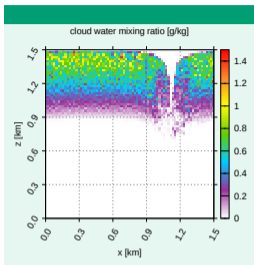
# przykładowa symulacja chmury (2D)



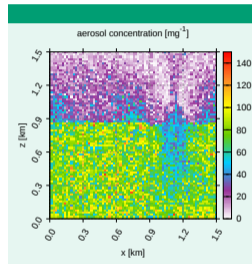
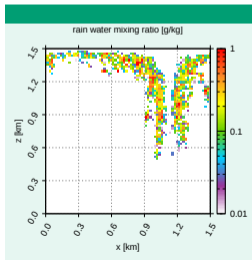
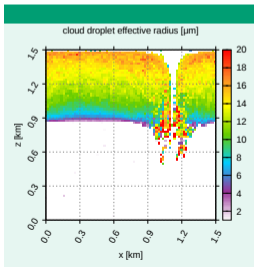
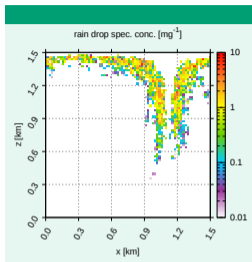
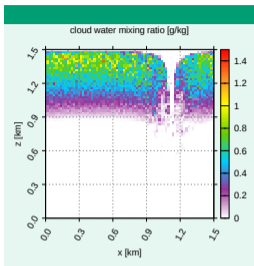
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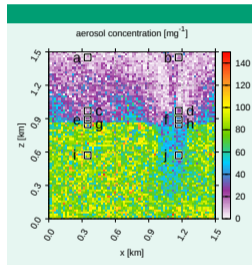
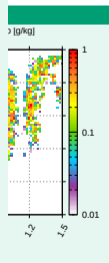
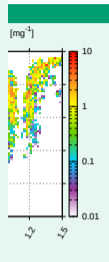
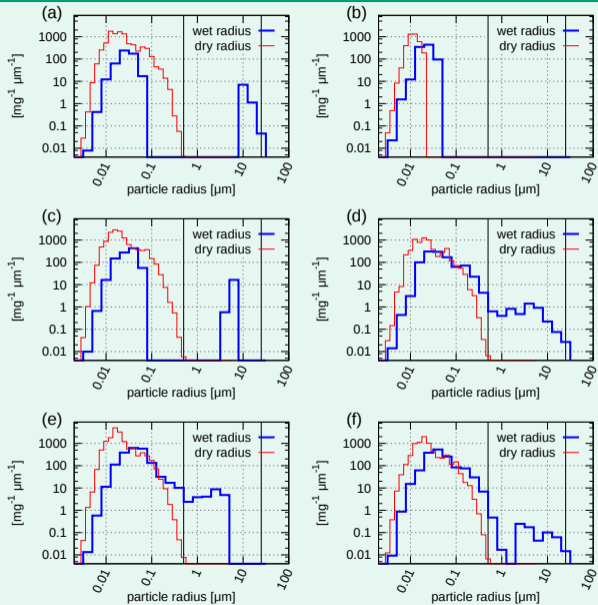
# przykładowa symulacja chmury (2D)



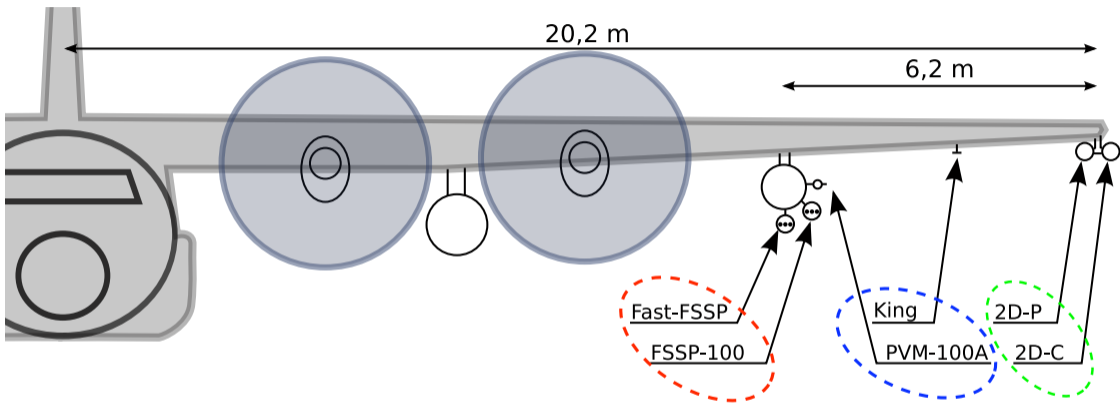
# przykładowa symulacja chmury (2D)



# widma rozmiarów cząstek



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



- ❑ 19 ok. 8-godzinnych lotów badawczych
- ❑ 5–10% czasu lotu wewnątrz chmur
- ❑ loty nad powierzchnią oceanu

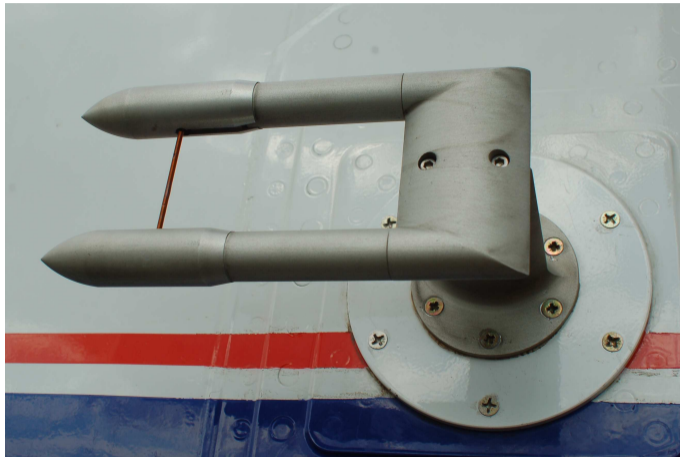
- ❑ spektrometria rozmiarów kropeł chmurowych
- ❑ pomiary całkowitej zawartości wody
- ❑ spektrometria rozmiarów kropeł opadowych

# przyrządy lotnicze do pomiarów w chmurach



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

## przyrządy lotnicze do pomiarów w chmurach



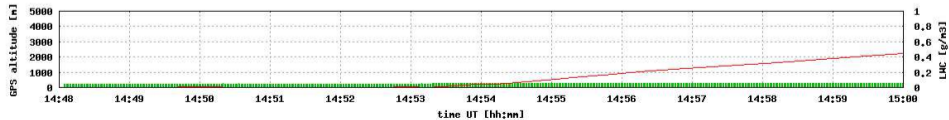
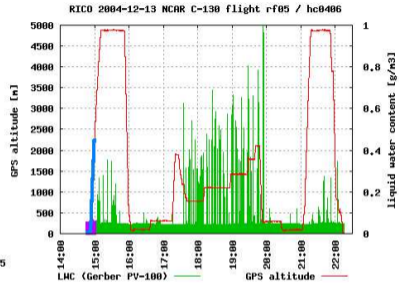
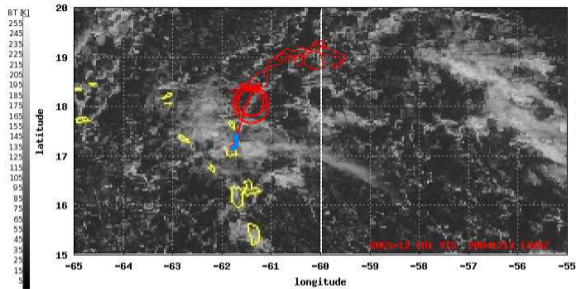
Instrument King-probe przymocowany do kadłuba samolotu ATR-42. (Jassy, Rumunia, 2007; fot. autor)

# przyrządy lotnicze do pomiarów w chmurach

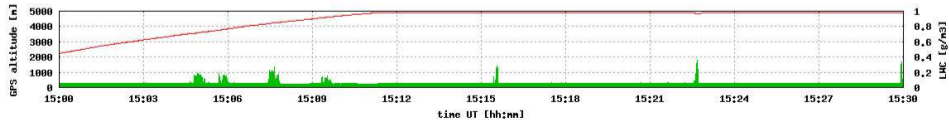
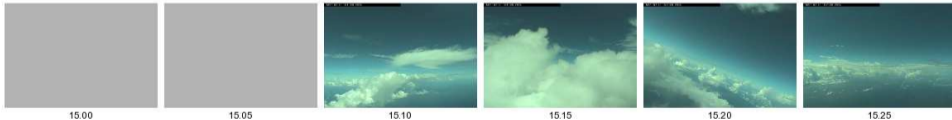
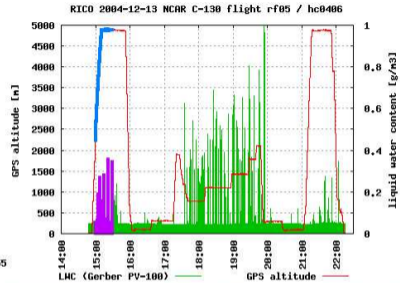
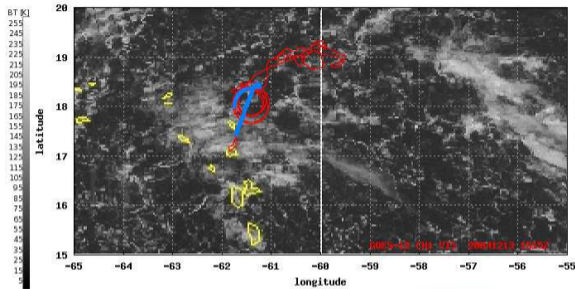


Instrument PVM-100A przymocowany do kadłuba samolotu ATR-42 (Jassy, Rumunia, 2007; fot. autor)

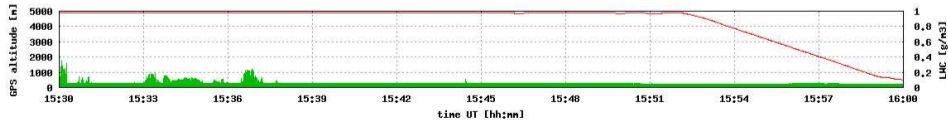
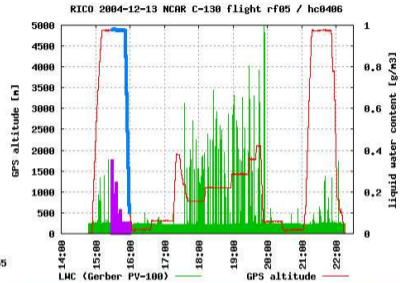
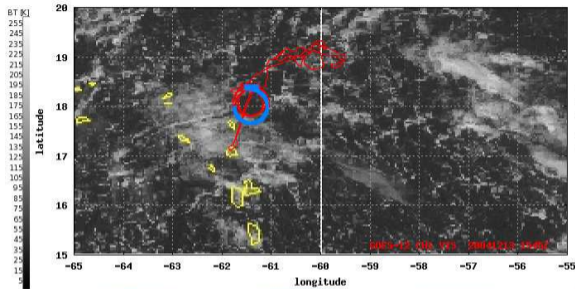
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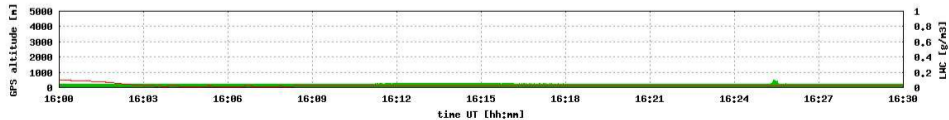
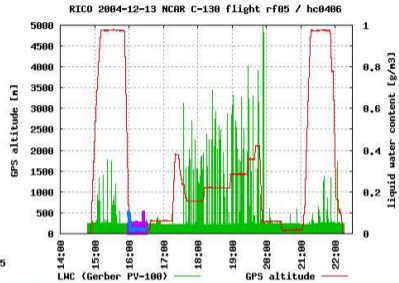
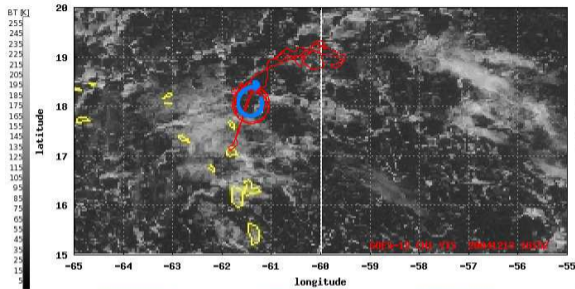
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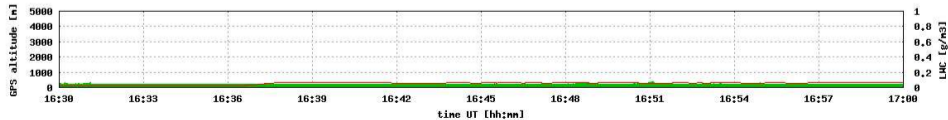
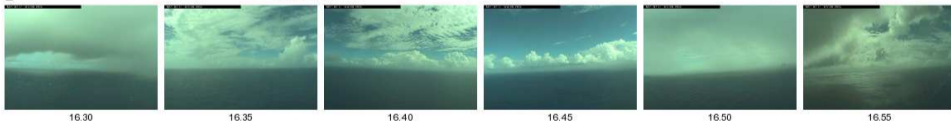
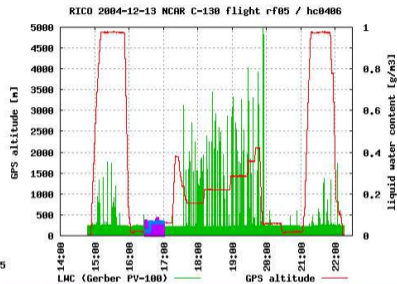
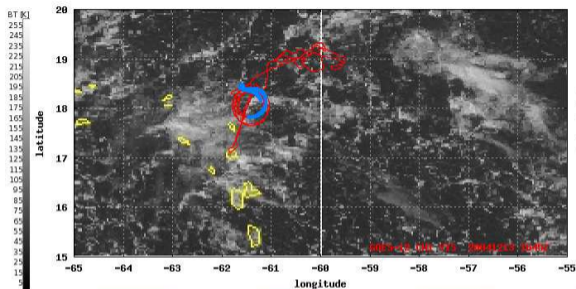
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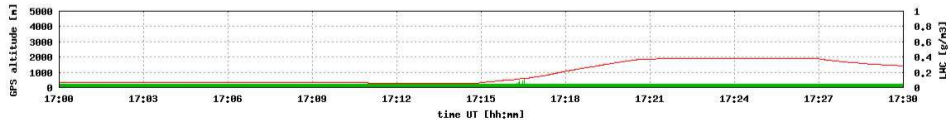
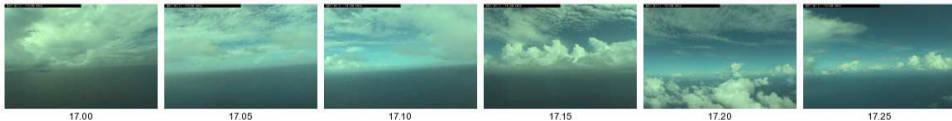
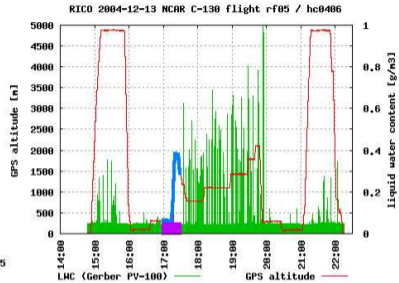
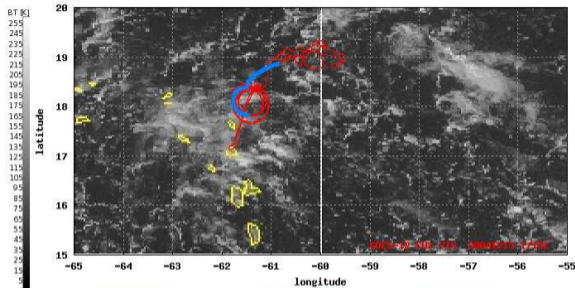
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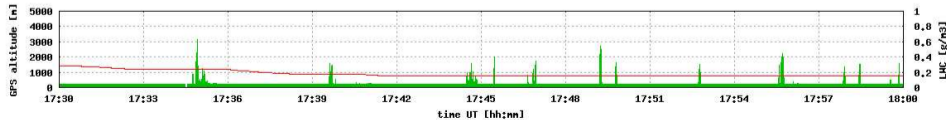
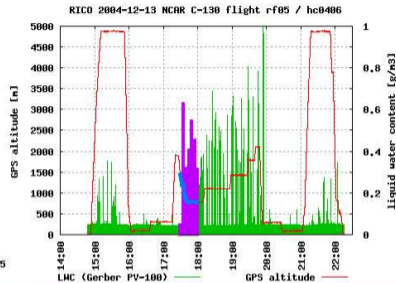
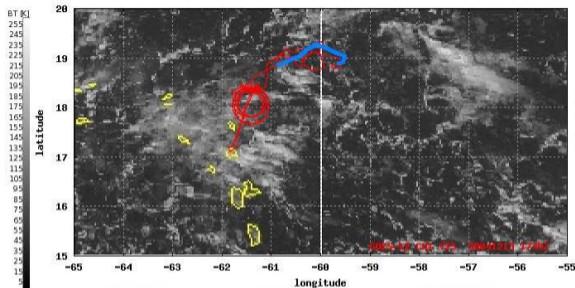
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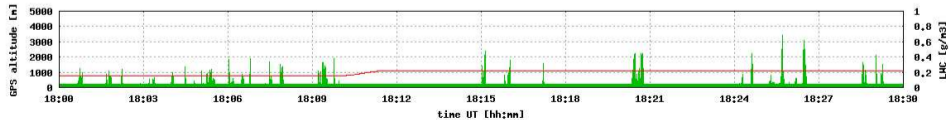
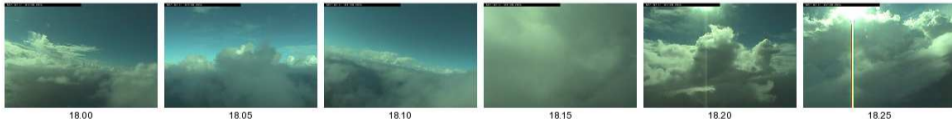
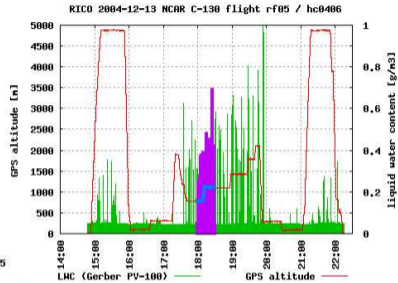
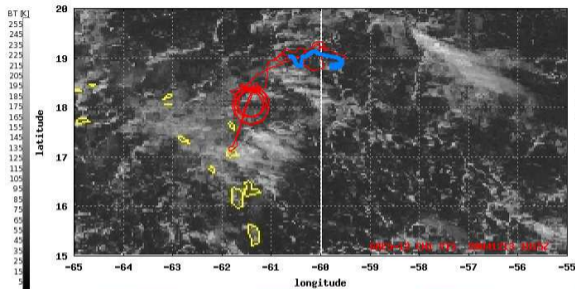
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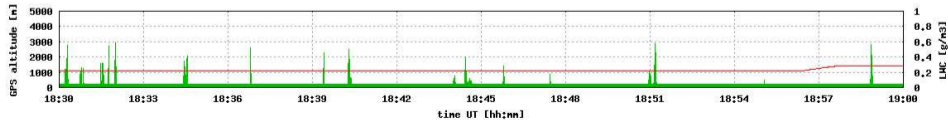
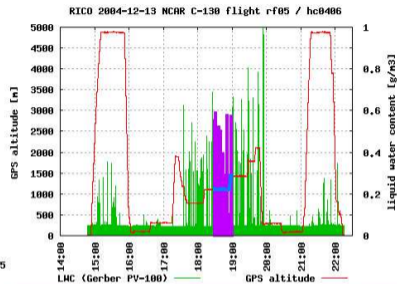
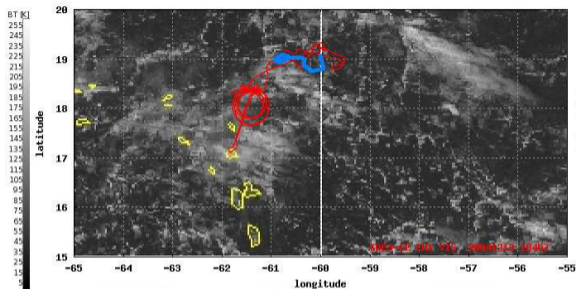
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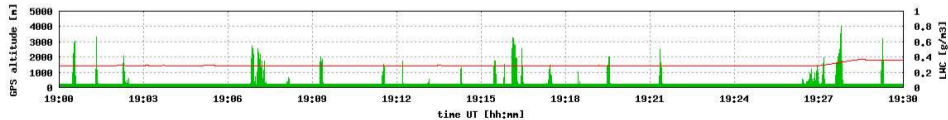
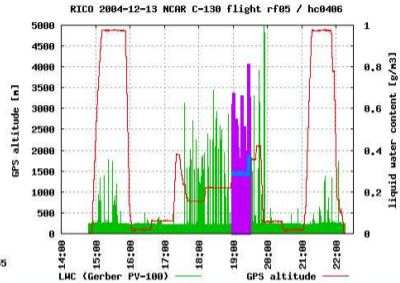
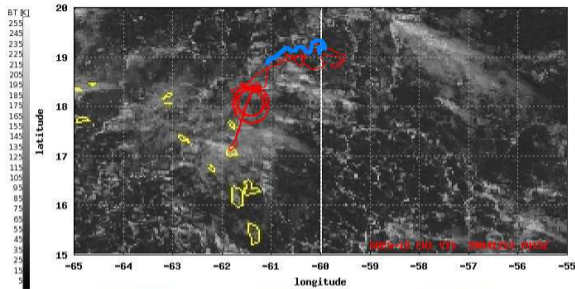
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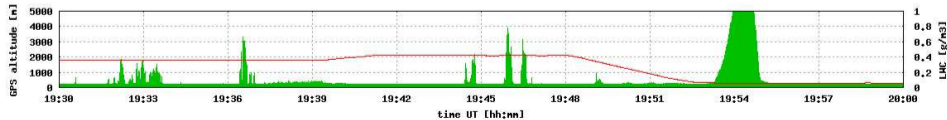
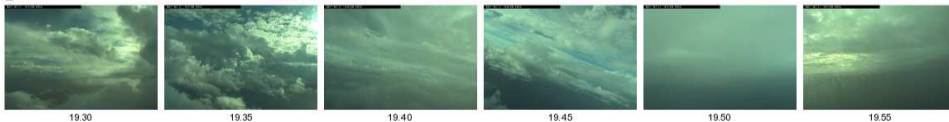
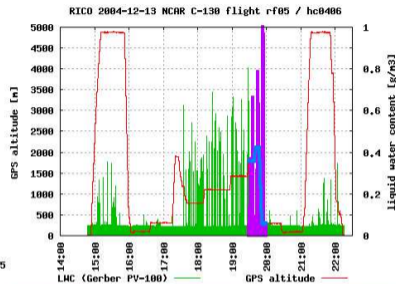
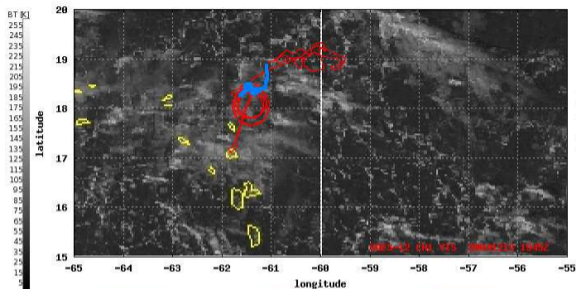
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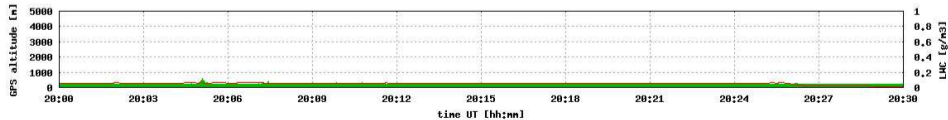
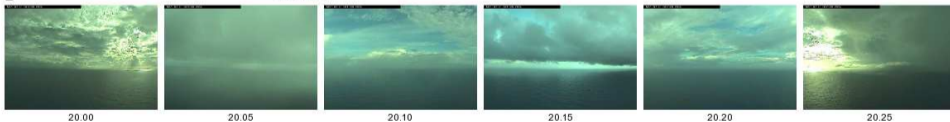
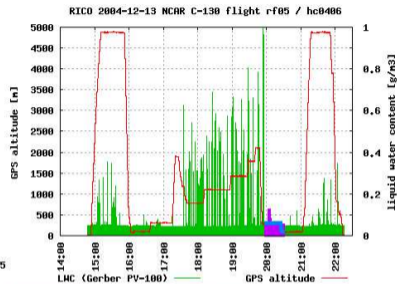
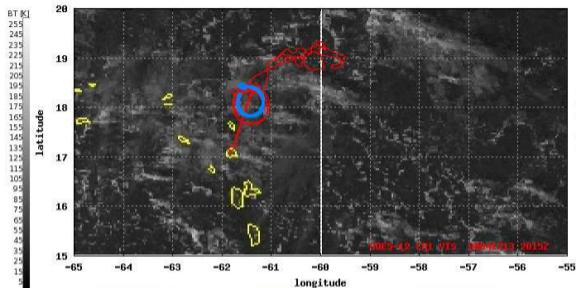
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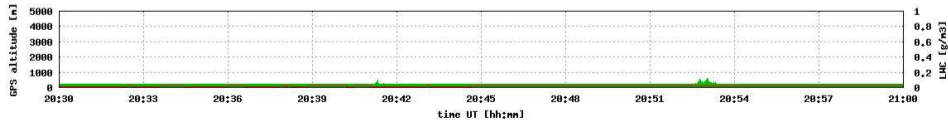
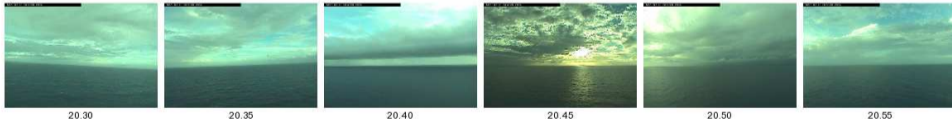
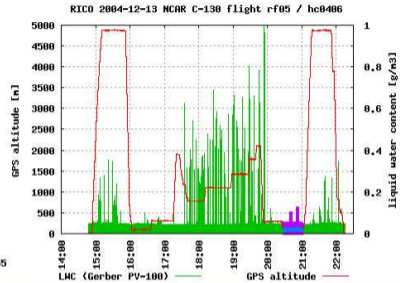
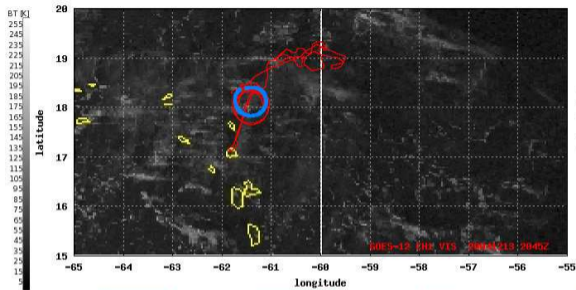
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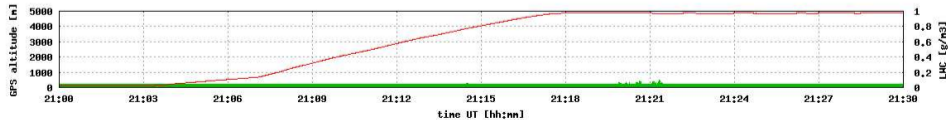
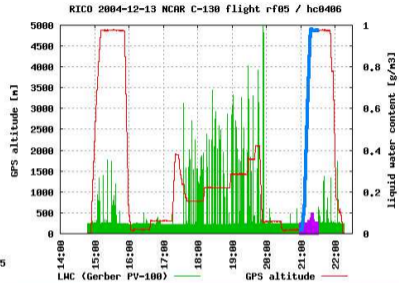
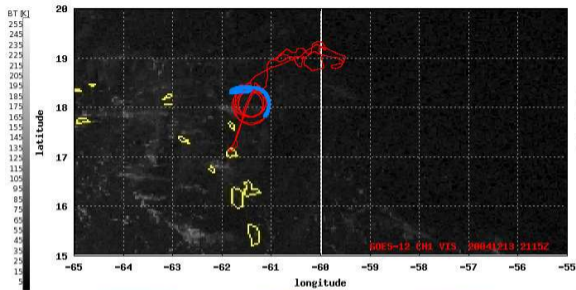
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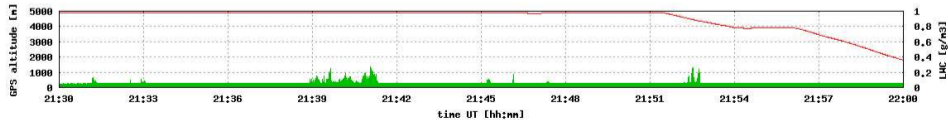
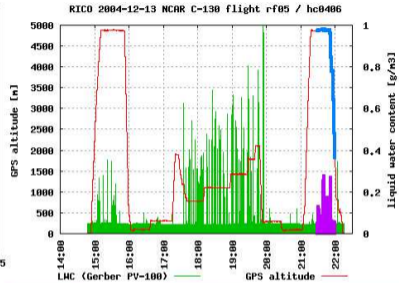
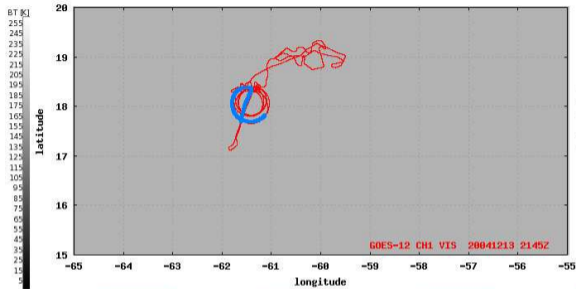
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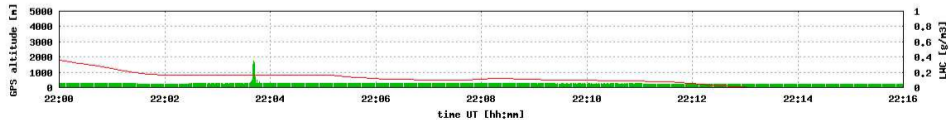
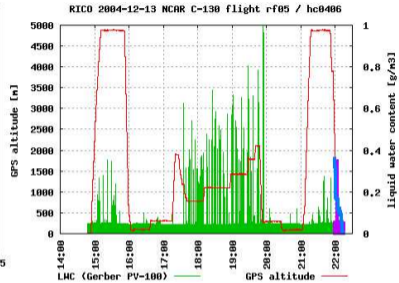
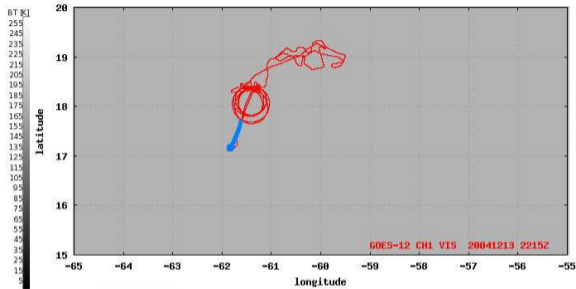
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# lot badawczy RICO: C-130 RF05



# lot badawczy RICO: C-130 RF05



## Exploring Cloud Microphysics Modeling Concepts the Pythonic Way

Sylwester Arabas<sup>a,\*</sup>, Agnieszka Żaba<sup>a,\*</sup>, Daria Klimaszewska<sup>a</sup>, Emma C. Ware<sup>b</sup>, Clare E. Singer<sup>c</sup>, Manhal Alhilali<sup>d</sup>, Jason Barr<sup>e</sup>, Daniel G. Partridge<sup>f</sup>, Shin-ichiro Shima<sup>d</sup>, Robert Wood<sup>e</sup>

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<sup>b</sup>*Department of Land, Air, and Water Resources, University of California Davis, Davis, CA, USA,*

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<sup>f</sup>*Department of Mathematics and Statistics, University of Exeter, Exeter, UK,*