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A 6 year climatology of fronts and their boundary layer structure in Helsinki

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Thanks t o Pasi Aalto, Ari Aaltonen, Leena Järvi and Eveliina Tuovinen

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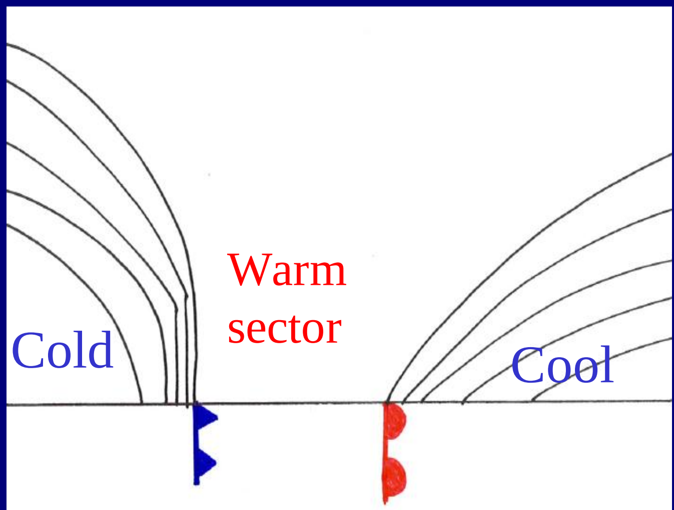
What is the definition of a front?

- “the interface or transition zone between two air masses of different density.” AMS Glossary
- “are transition zones separating air masses having different origins within which the horizontal temperature (and density) gradient is greatly enhanced relative to the larger scale meridional temperature gradient” Markowski & Richardson p115
- Note that neither definition refers to wind patterns.



Surface fronts are analysed on the warm side of the thermal gradient for both warm and cold fronts.

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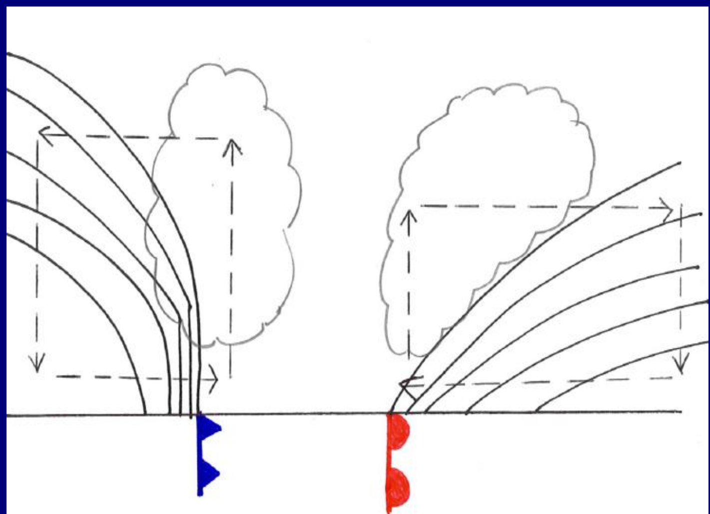
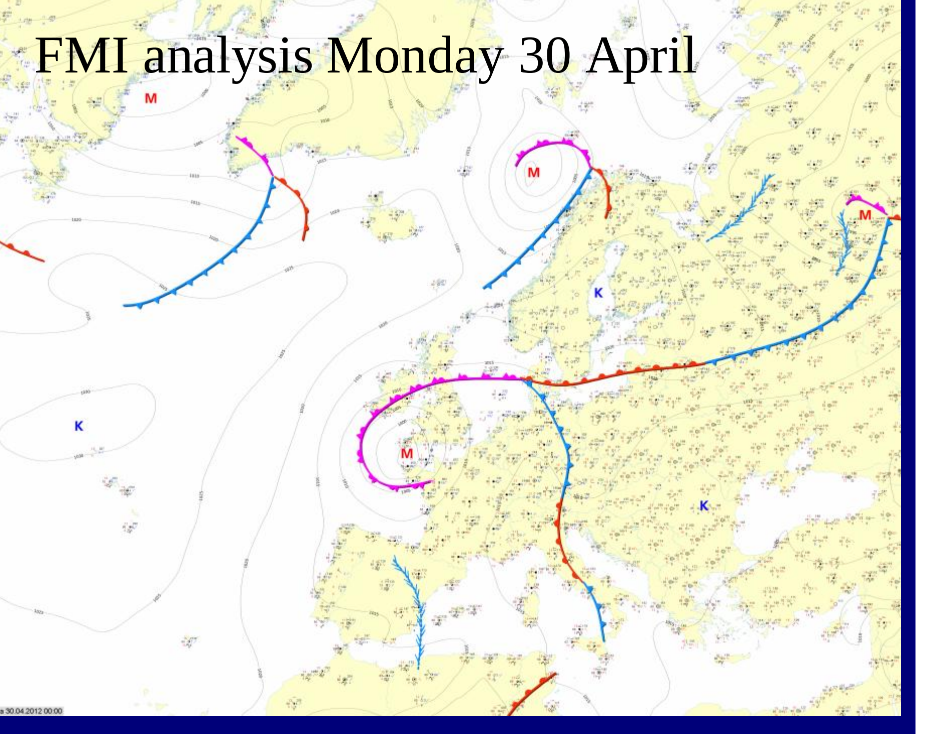


Surface fronts are analysed on the warm side of the thermal gradient for both warm and cold fronts.

Why are fronts important?

- Critical in determining the weather in mid-latitudes
- Can cause hazardous weather
  - Strong winds, heavy snow, initiate convection
- Can ventilate pollutants out of the boundary layer
  - Can affect local air quality
- Can transport pollutants long distances.



Why construct a climatology

- Very few frontal climatologies exist
- Results of seasonal and diurnal cycles in fronts may be useful for
  - Forecasters
  - General atmospheric research – can relate case studies to average conditions
  - To assess the effect of climate change on weather patterns.
- No climatologies of frontal structures based on observations
- Limited knowledge of the boundary layer structure of fronts
  - Potentially at the end of the storm tracks and at 60N fronts have different structures to elsewhere (e.g. North America, Australia, UK)

Questions to address

SYNOPTIC-SCALE

1. How often to warm, cold and occluded fronts affect Helsinki?
2. Do fronts affecting Helsinki exhibit a diurnal or seasonal cycle?

MESOSCALE

3. What is the average structure of a cold and warm front in Helsinki?
4. What factors influence the temperature change, amount of precipitation and vertical tilt of fronts?

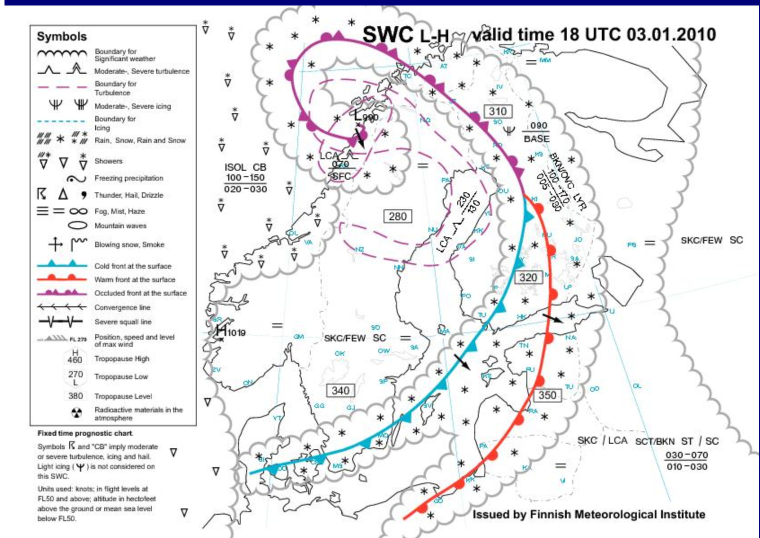
MICROSCALE

5. How does the passage of fronts modify the boundary layer structure?
6. What is the turbulent structure within frontal zones?

Data Sources

1st Jan 2006 – 31st Dec 2011

Significant Weather Charts



←Kivenlahtii mast

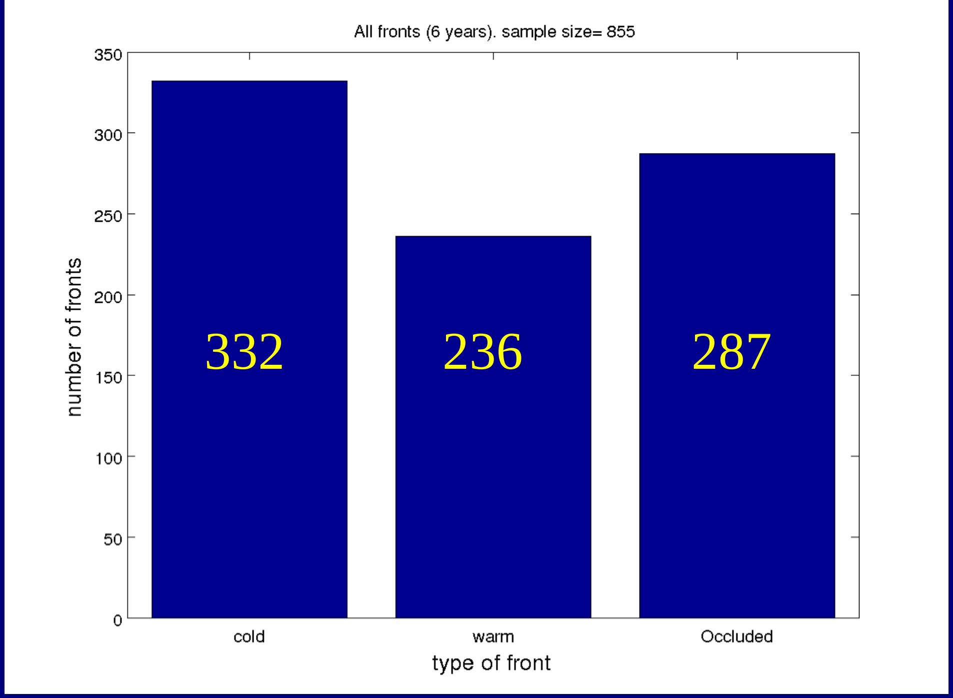
SMEAR III

SYNOPTIC SCALE → MESOSCALES → MICROSCALE

Synoptic Climatology database - SWCs

- All cold, warm and occluded fronts that moved over Helsinki are included.
- Fronts must appear on at least two consecutive analysis charts to be included
- The time of the front is taken to be the time of the SWC when the front is closest to Helsinki
  - No “interpolation” is done as it would be very subjective!
- The time and type of front and the direction that the front approached Helsinki from are included in the database.

Helsinki front climatology statistics



Cold fronts are the most common, then occluded fronts and warm fronts are the least common.

Cold front every 6.6 days

Occluded front every 7.6 days

Warm front every 9.3 days

One front every 2.6 days

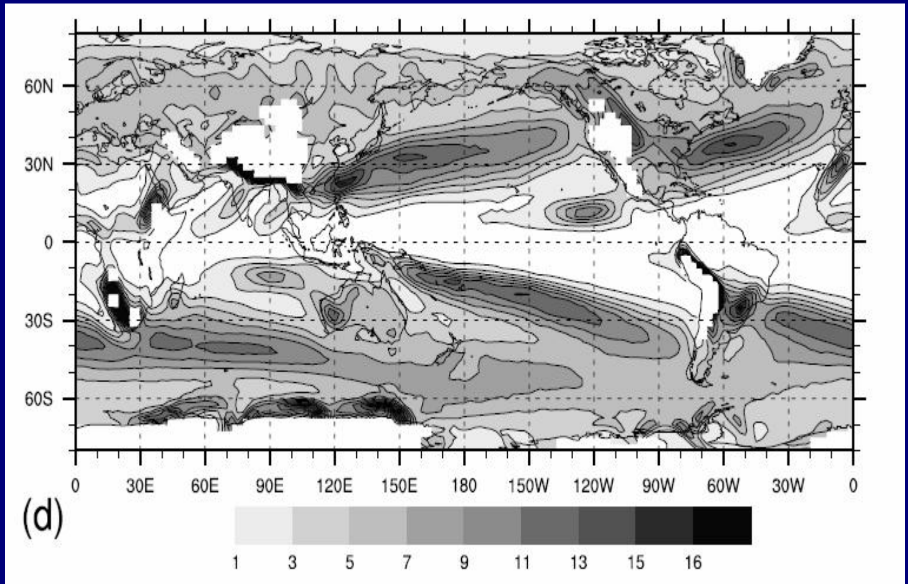
Type of front	total number	fronts per year	St. Dev.	median
Cold	332	55.3	6.6	55
Warm	236	39.3	6.2	38
Occluded	287	47.8	6.7	48
Total	855	142.5	15.9	138

Comparison to previous studies

Helsinki

Cold fronts : 1 per 6.6 days
Warm fronts: 1 per 9.3 days
Occlusions : 1 per 7.6 days

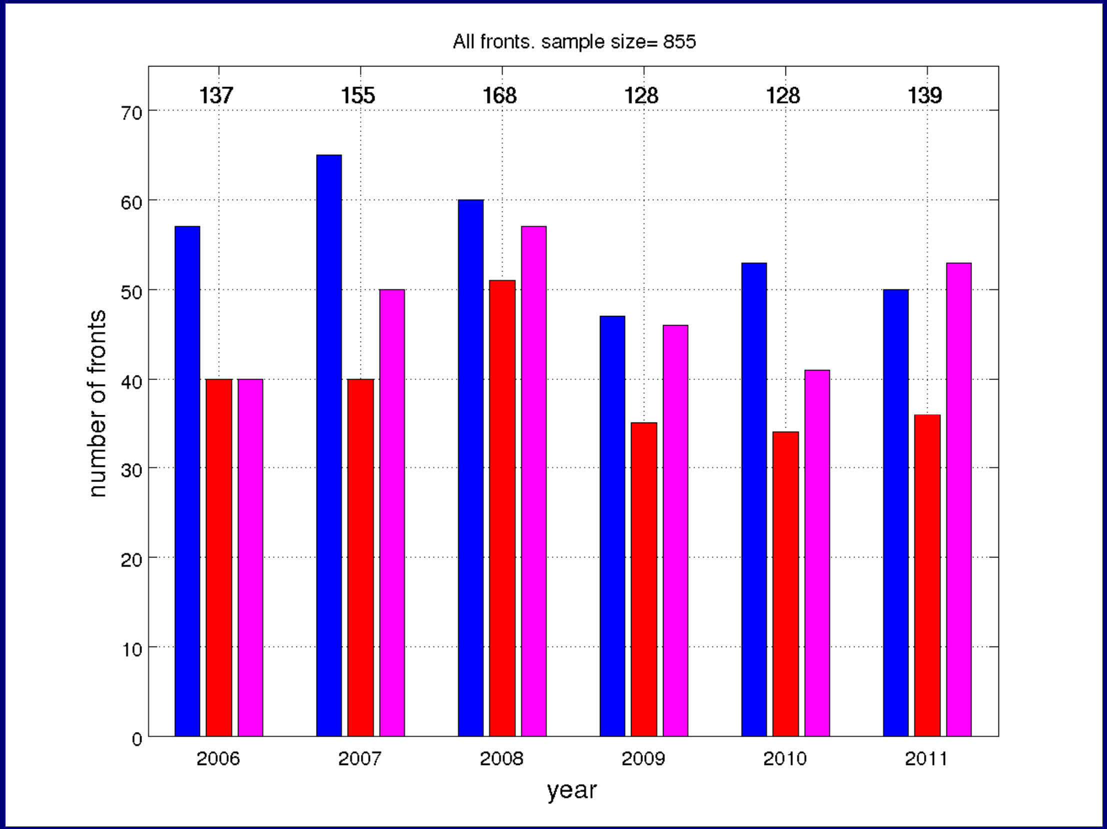
Frontal Frequency. ERA-40. 850hPa



Berry et al. (2011) GRL

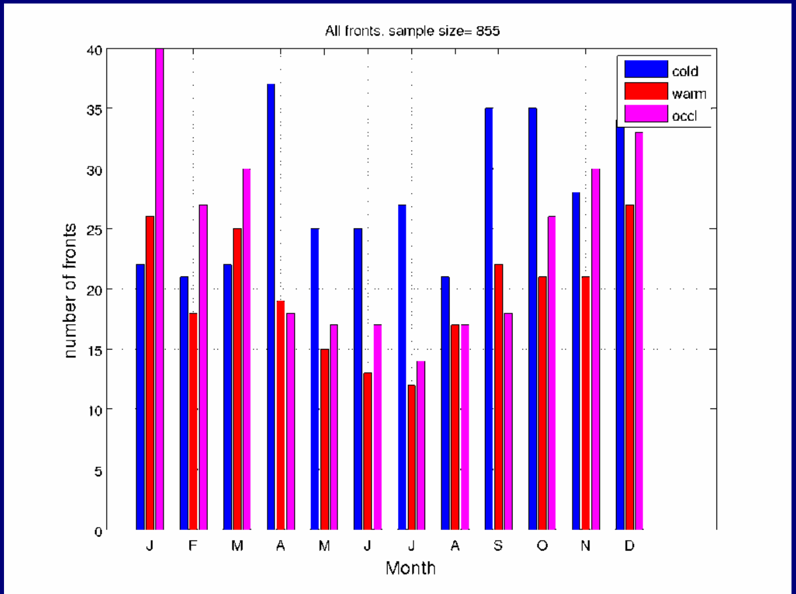
- Hoinka (1985) - Munich
  - Cold fronts: 1 per 6.7 days
  - Warm fronts: 1 per 19.2 days
  - Very few occlusions
- Jenker et al (2010) – European Alps
  - Warm fronts: 1 per 7 days
  - Cold fronts : 1 per 7 days
- Payer et al. (2011) - Great Lakes
  - Cold fronts were the most common
- Berry et al. (2011) – Global
  - In southern Finland, one front per 20 – 33 days.

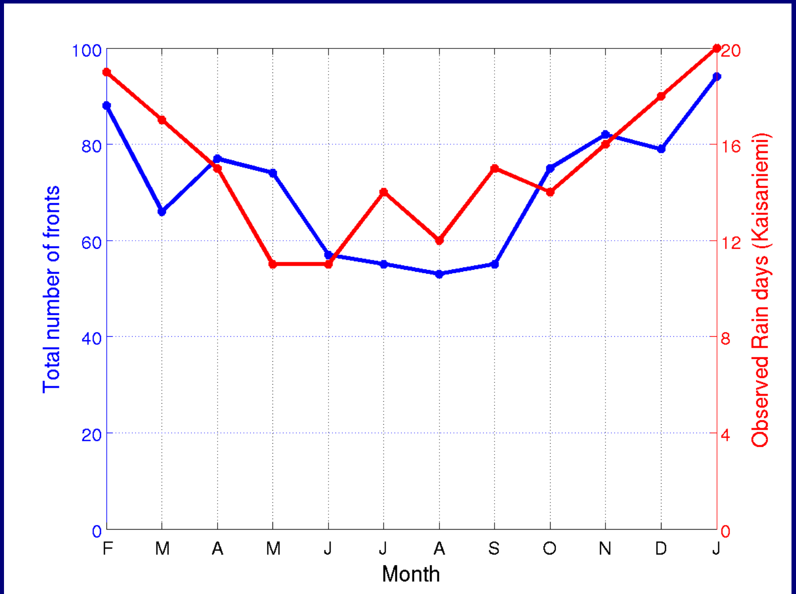
Annual variability in frontal type



- 2007 and 2008 had the most fronts
- Both years had warm winters – more westerly flow
- 2008 was wetter than average

Seasonal cycle of fronts



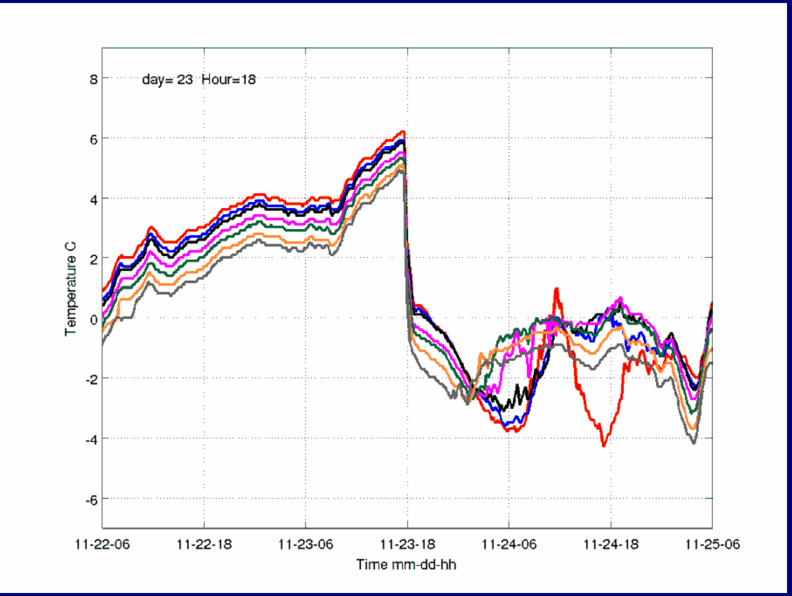


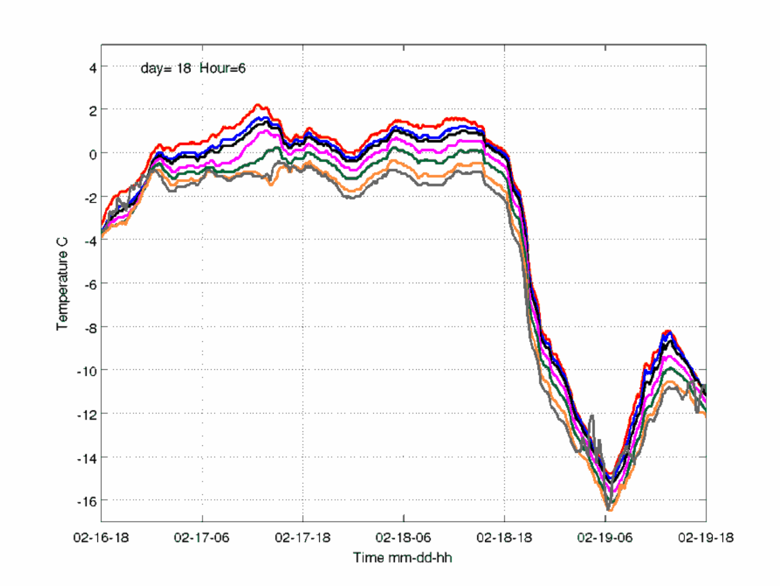
- Most fronts occur between September – April
- Cold fronts have a weaker seasonal cycle than warm and occluded fronts
- Minimum in February - anticyclonic blocking patterns?
- Strong correlation with observed number of rain days

Climatology of frontal structures within the boundary layer

Analyse Kivenlahti mast observations

Kivenlahti mast data

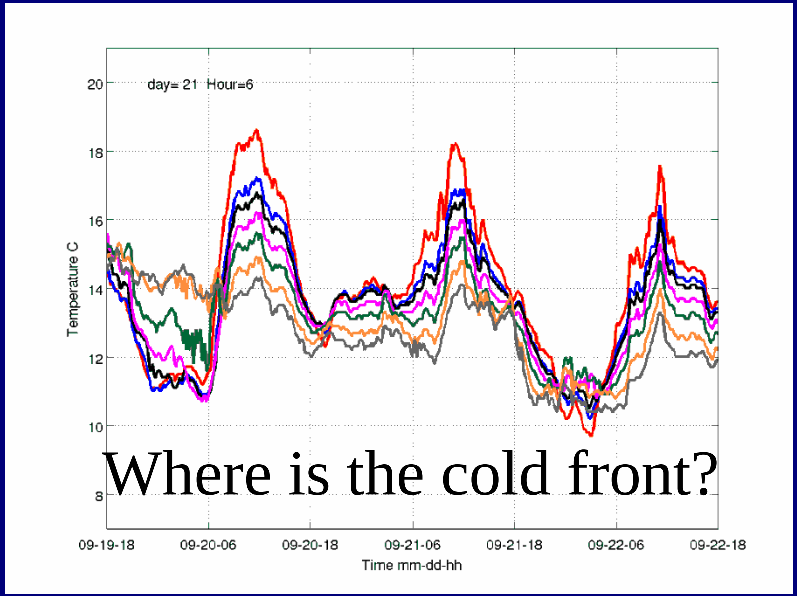


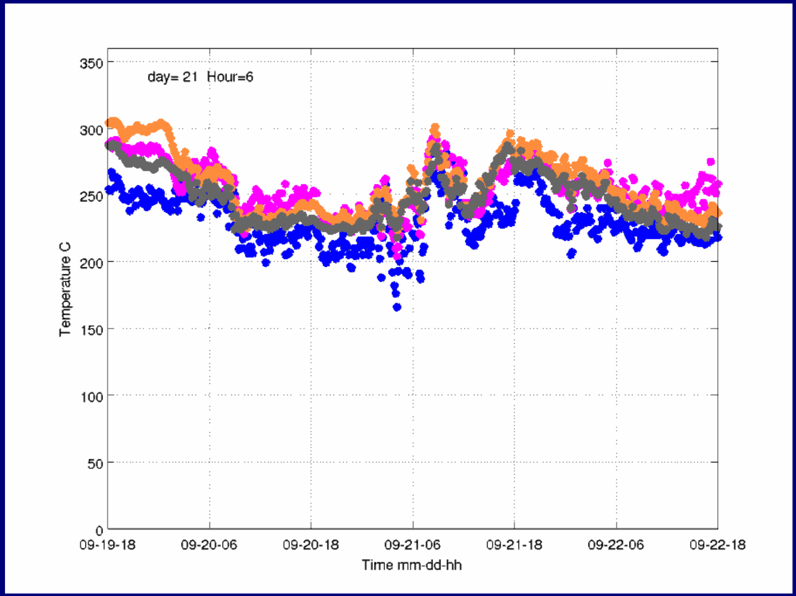


For all warm and cold fronts the following was obtained and added to the database:

1. The exact time of each front (start and end)
2. Temperature change
3. Wind direction change
4. Wind speed change
5. Lapse rate ahead of the front

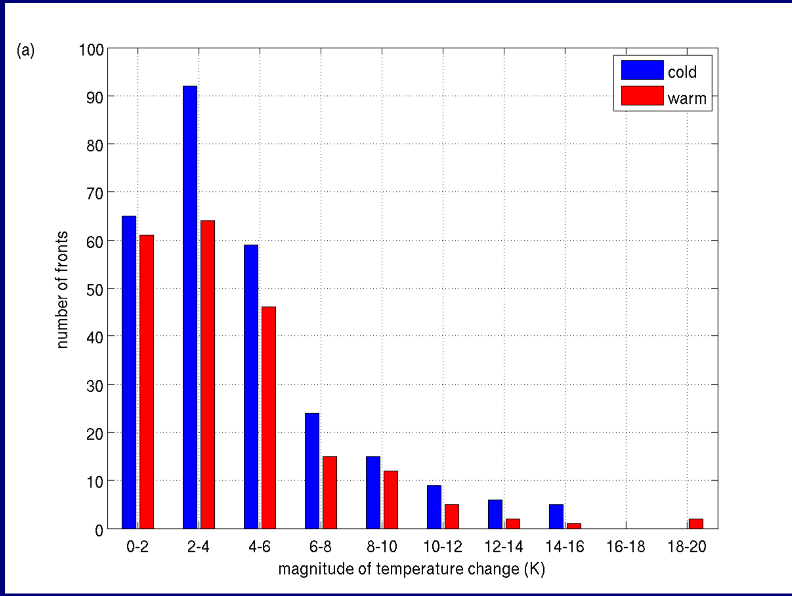
Some analysed fronts were difficult to find in the observations

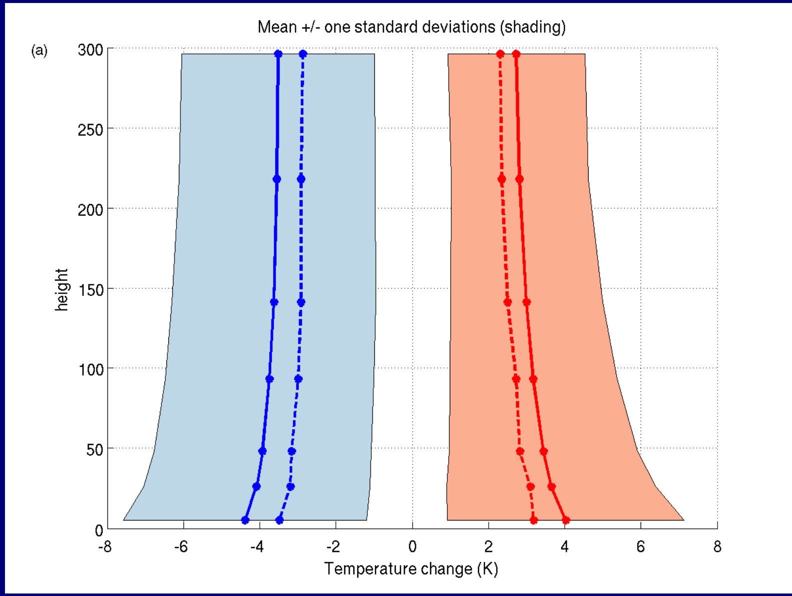




- Especially true in the summer when diurnal cycles are large
- Almost all analysed fronts had at least a weak wind shift in the observations.
- Cold fronts: 23/332 had missing data. 35/332 could not be identified in observations
- Warm fronts: 17/236 has missing data: 8/236 could not be identified

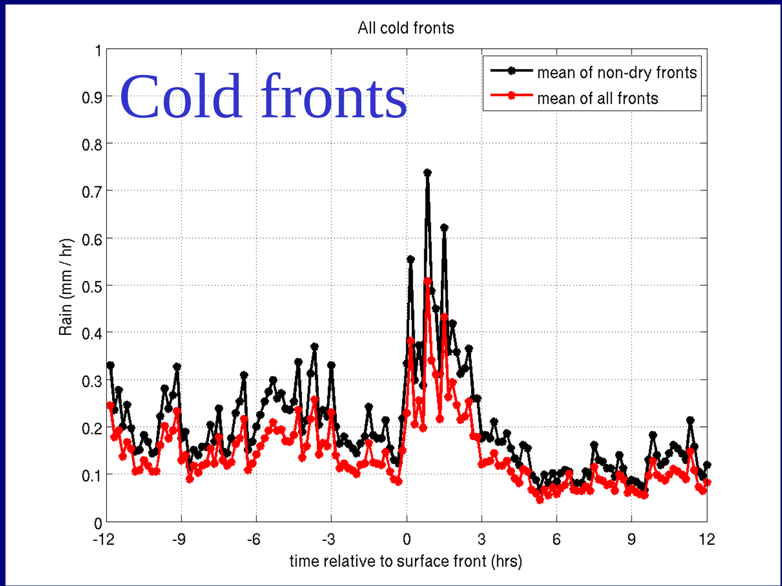
Average front: temperature change

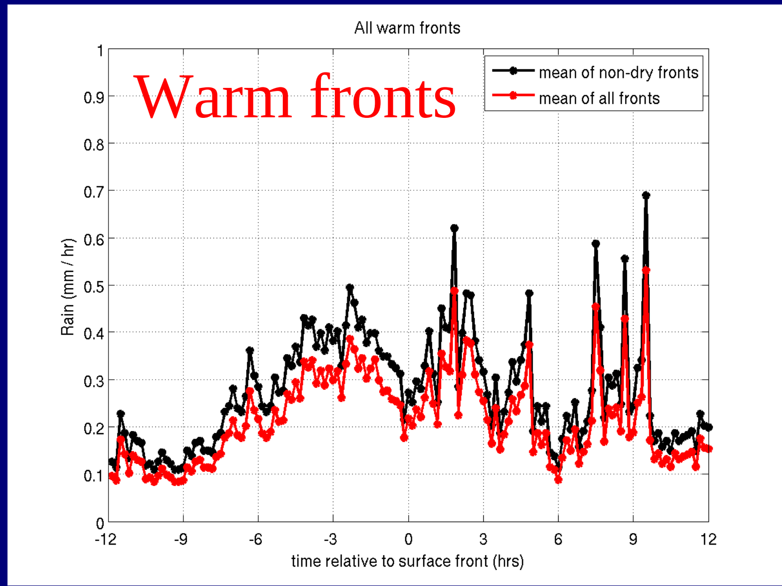




- Average cold front in Helsinki: -4.4C
- Average warm front in Helsinki: +4.0C
- Temperature change due to fronts is a strongly positively skewed distribution
- Temperature change is largest at the surface.

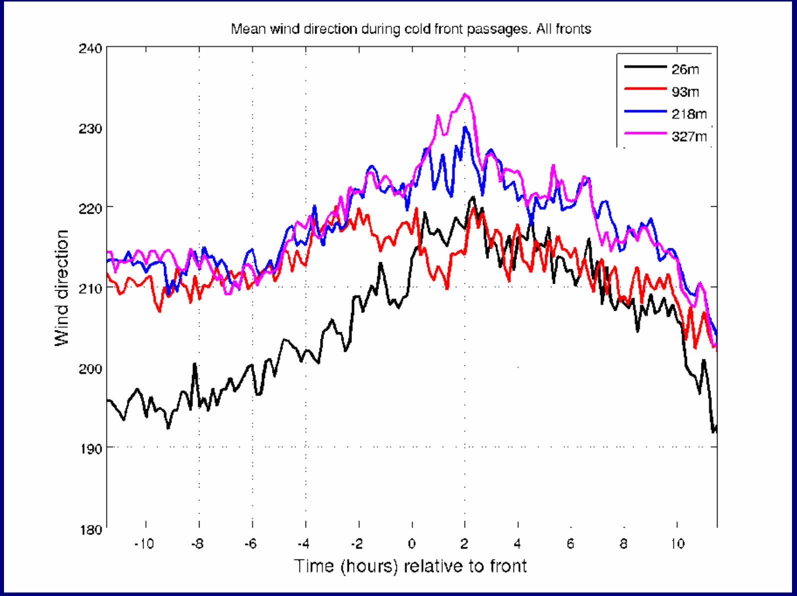
Average front: precipitation (rain rates)

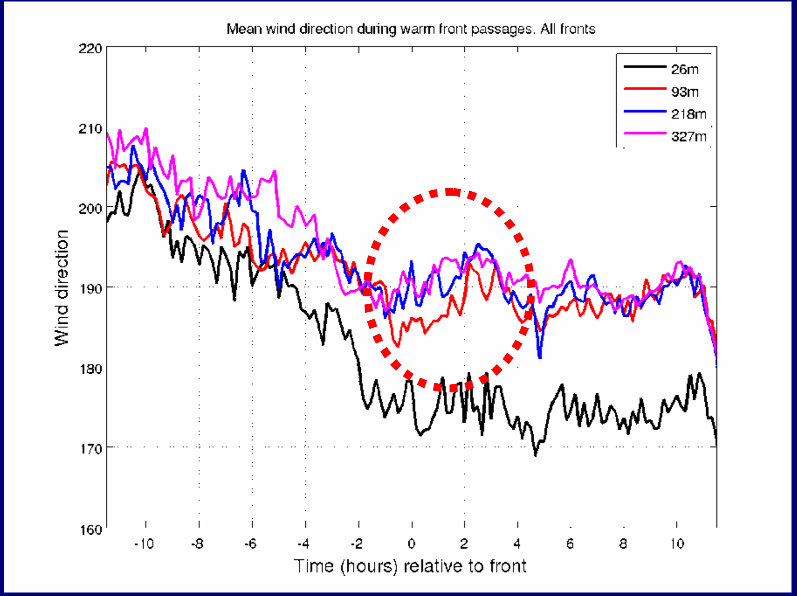




- Cold fronts have most rain during the 3 hours after the front
- Warm fronts have large amounts of rain both ahead of and behind the surface front.
- Cold fronts produce heavier rain rates, but not more total rainfall

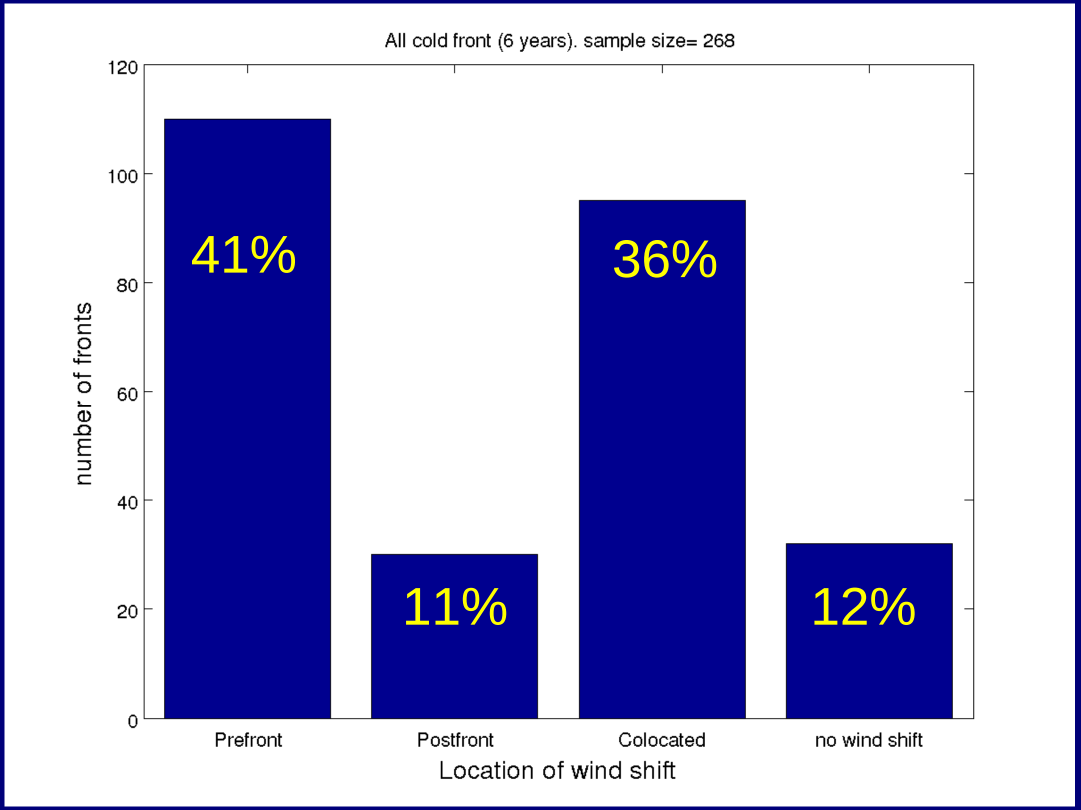
Average front: wind direction change





- Cold fronts typically have SSW winds ahead and then SW winds behind. Average wind shift ~25 degrees
- Warm fronts have a less clear signal
  - Strong veering from -12 hrs to -2hrs
  - Weaker backing from -2 hrs to +3 hrs
  - Wind shift ~10 degrees

Location of wind shift relative to front

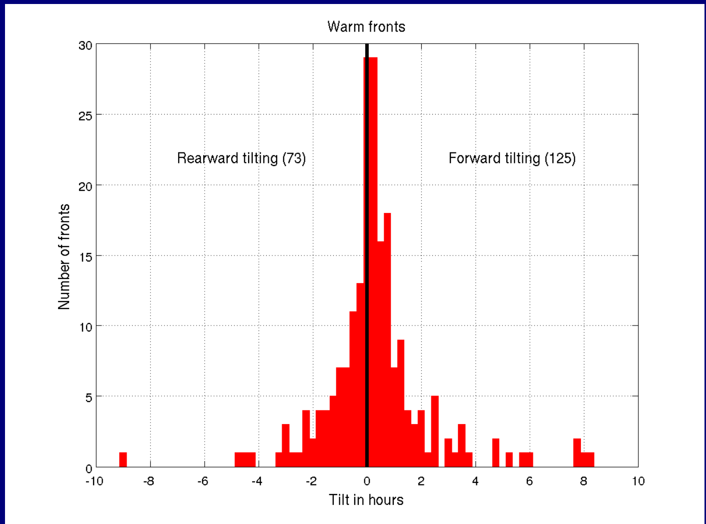


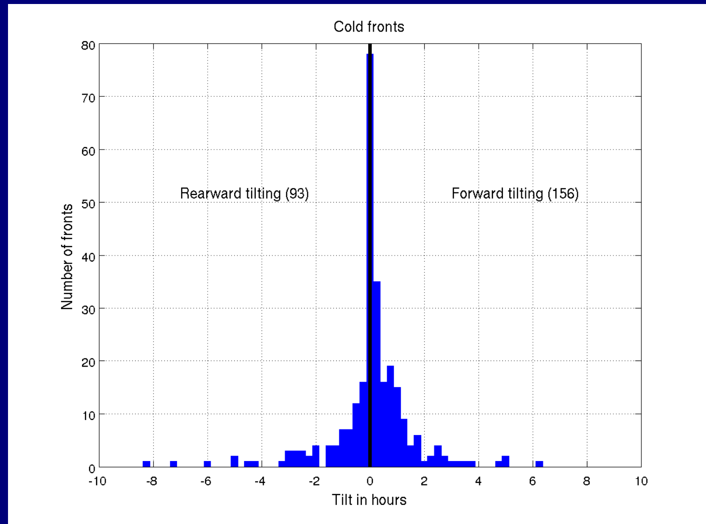
For COLD FRONTS ONLY

Wind shifts ahead of the thermal gradient are slightly more common than co-located wind shifts

The vertical tilt of fronts

$$Tilt = time(5m) - time(296m)$$

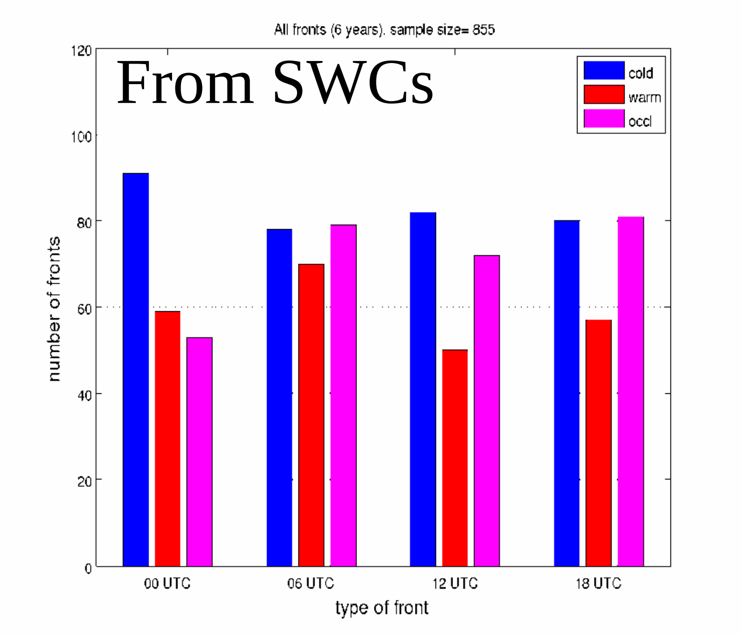


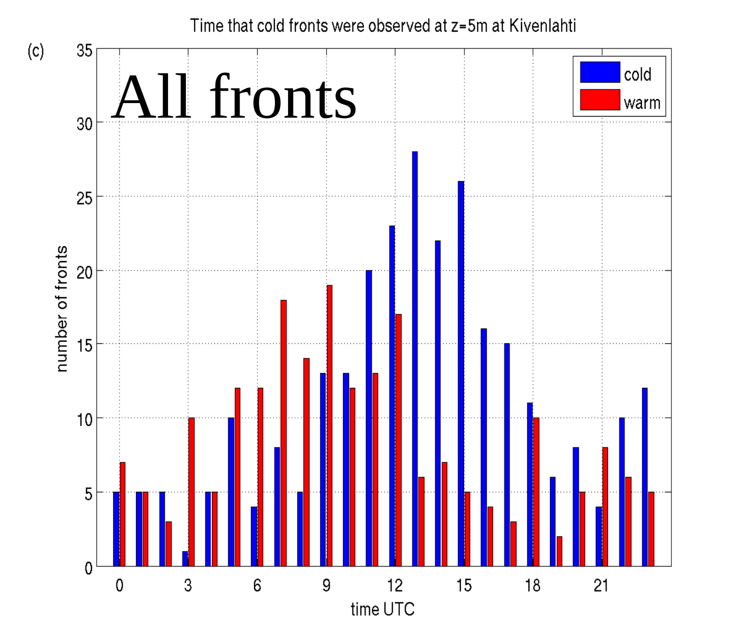


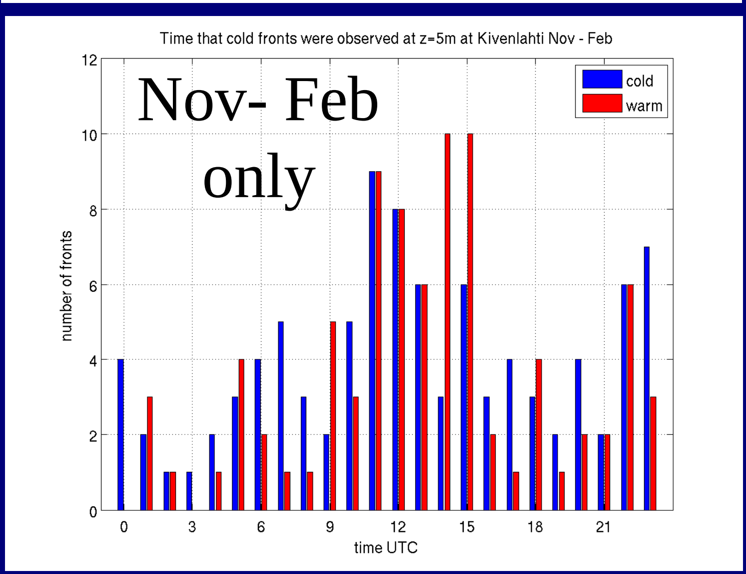
- Conceptual models tell us the warm fronts tilt forward with height and cold fronts tilt rearward with height
- Within the lowest 300m, both warm and cold fronts tilt forward with height more often than rearwards with height.
  - Friction retards the front at the surface
- Cold fronts are more vertical than warm fronts
- 26 cold fronts were totally vertical and 10 warm fronts

Diurnal cycle

From Kivenlahti Observations





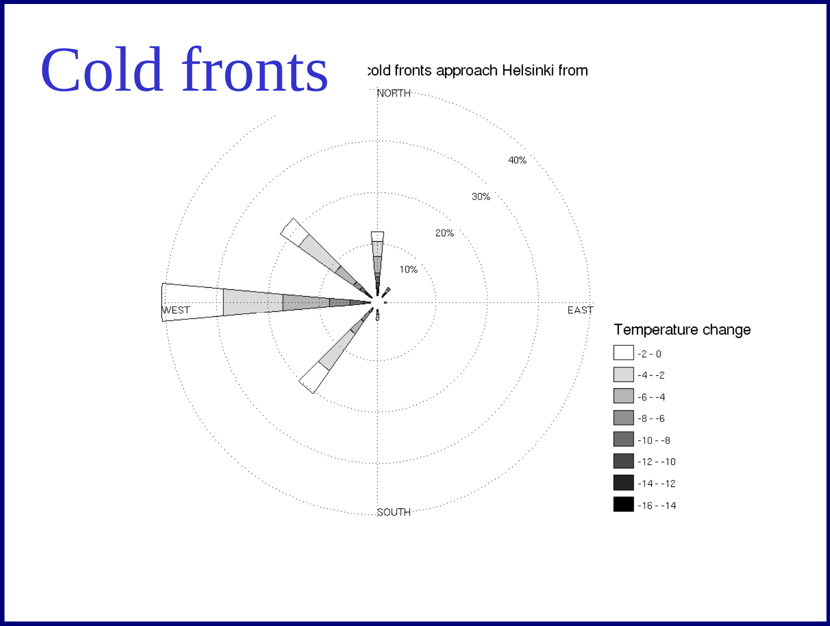


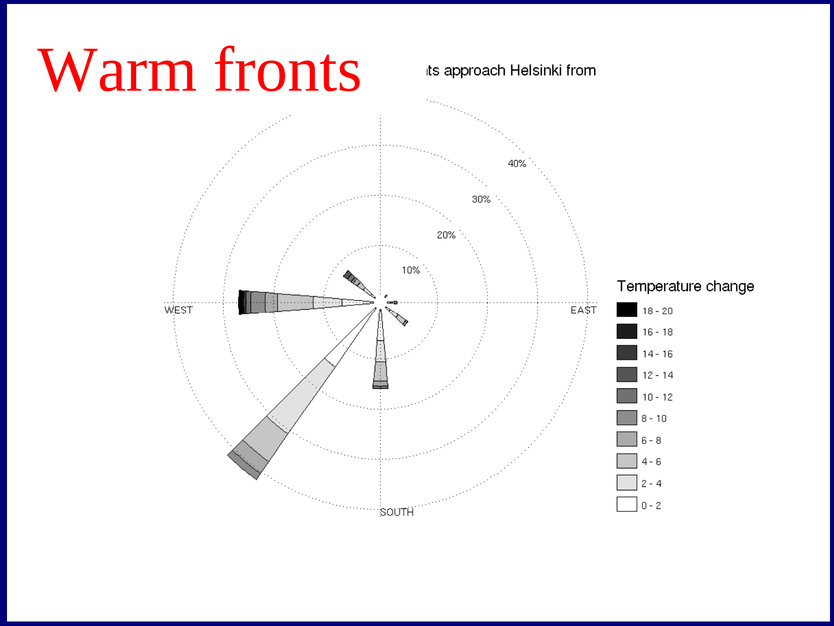
- Observations suggest a diurnal cycle but SWCs do not
- Are land and sea breezes accidentally identified in the observations as fronts?

What factors determine the observed structure of fronts?

e.g. Is the temperature change due to a front determined solely by synoptic scale processes or do mesoscale and boundary layer processes play a role?

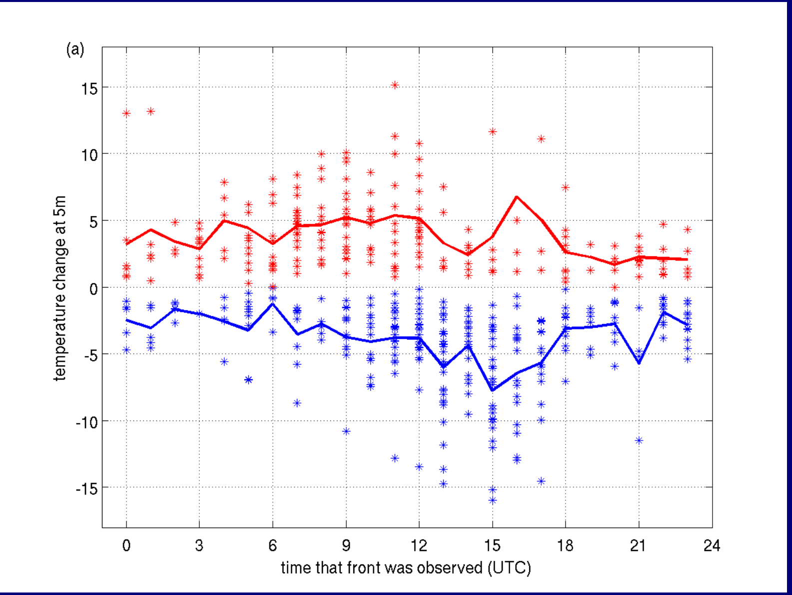
Does the temperature change depend on the direction that the front approached Helsinki front?

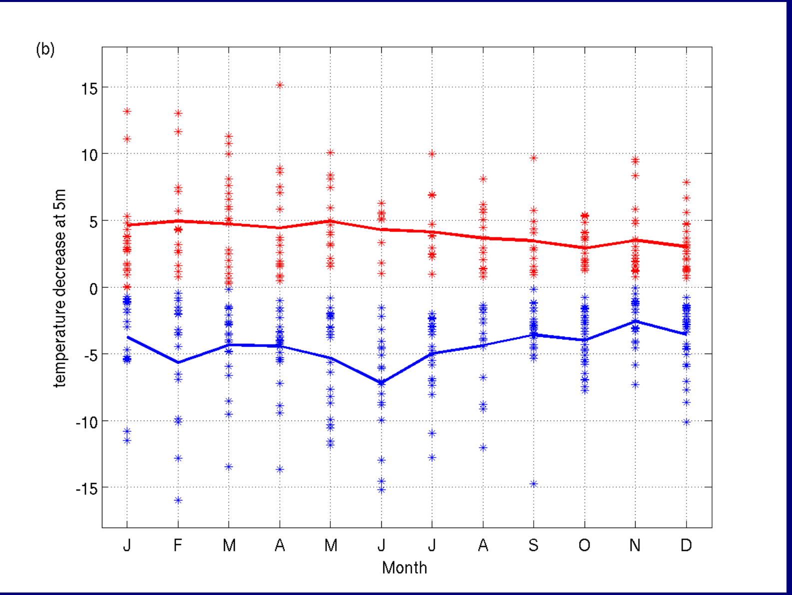




- Cold front which approach from the north and north-west are more likely to have large temperature decreases
- The strongest warm front approach from the west and north-west

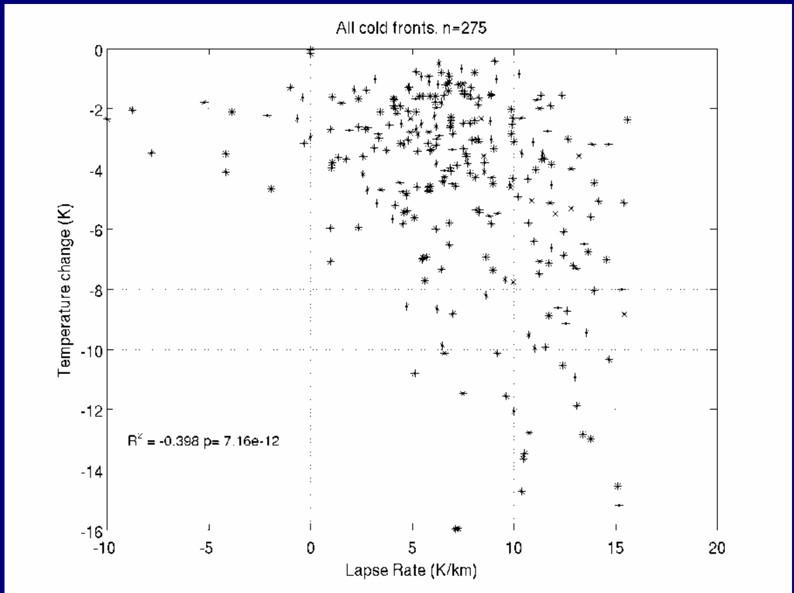
Does temperature change depend on time of day or month?

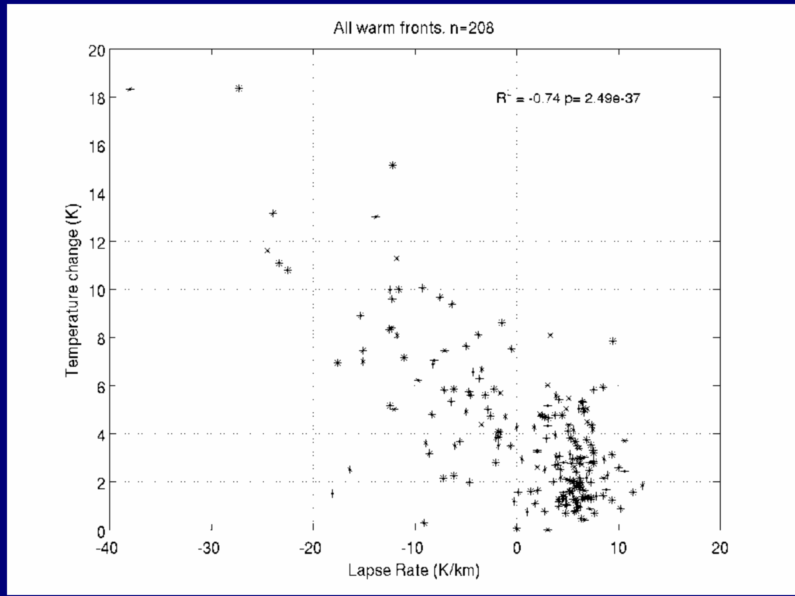




- No seasonal cycle in the temperature change
- Strongest cold fronts occur in late afternoon

How does the low-level stratification ahead of the front affect the temperature change?



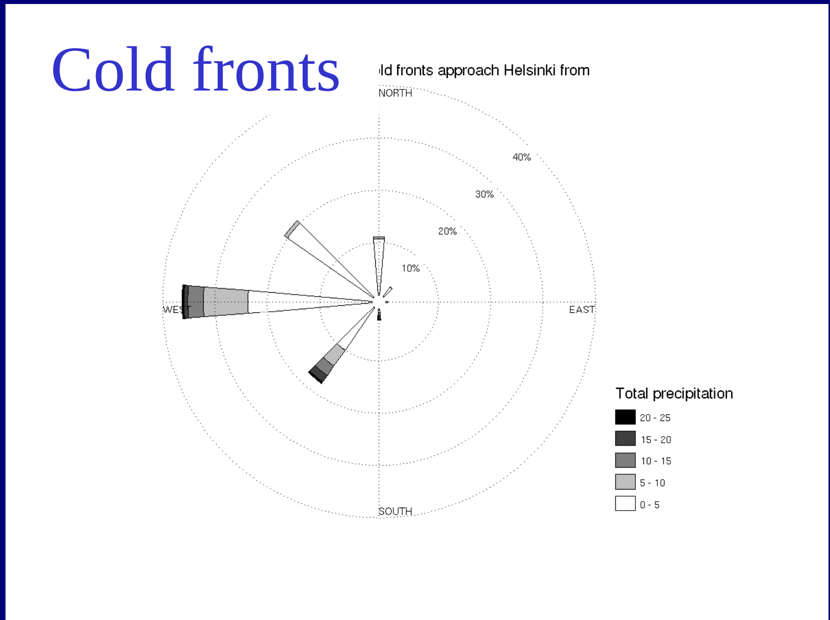


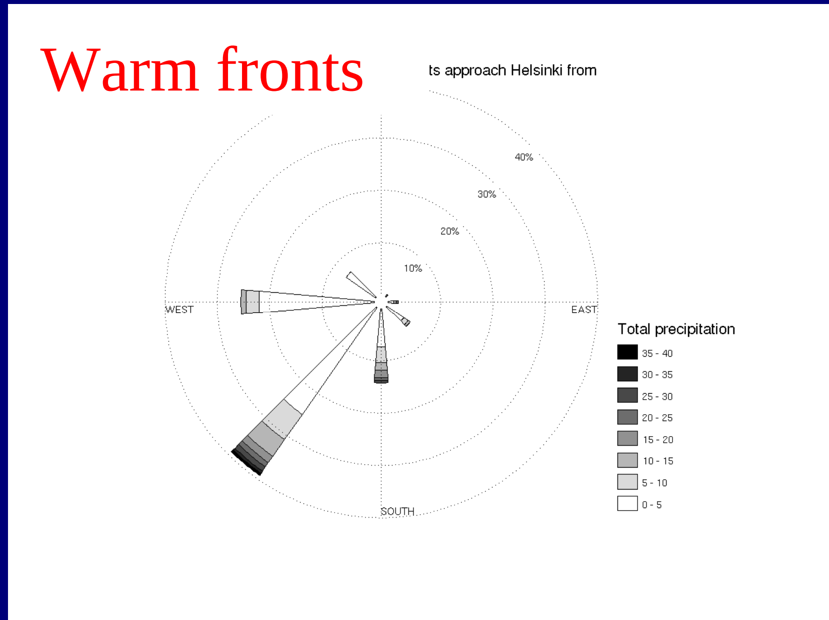
Cold fronts

Warm fronts

- The strongest cold fronts occur when the prefrontal BL is unstable
    - Positive heat fluxes ahead of front increase low level temperature → diabatic frontogenesis
- Strongest warm fronts occur when prefrontal BL is strongly stable
    - Negative heat fluxes ahead of the front → diabatic frontogenesis
    - Fronts can destroy inversions and mix warmer air down from above

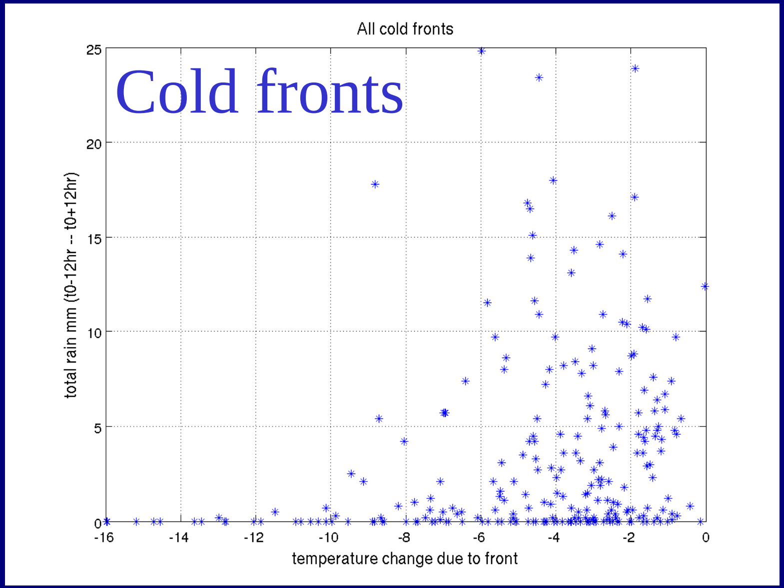
Does precipitation depend on direction that fronts approach Helsinki from?

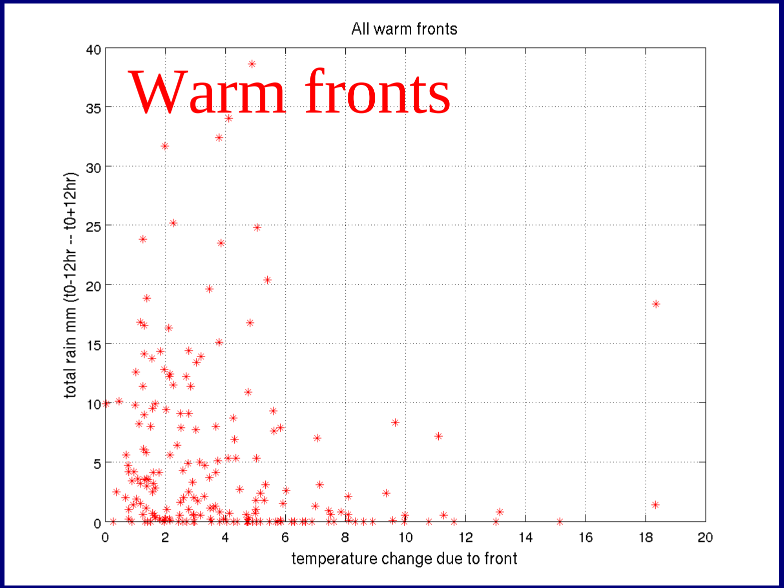




- Both warm and cold fronts produce the most precipitation if they approach from the south or south-west.

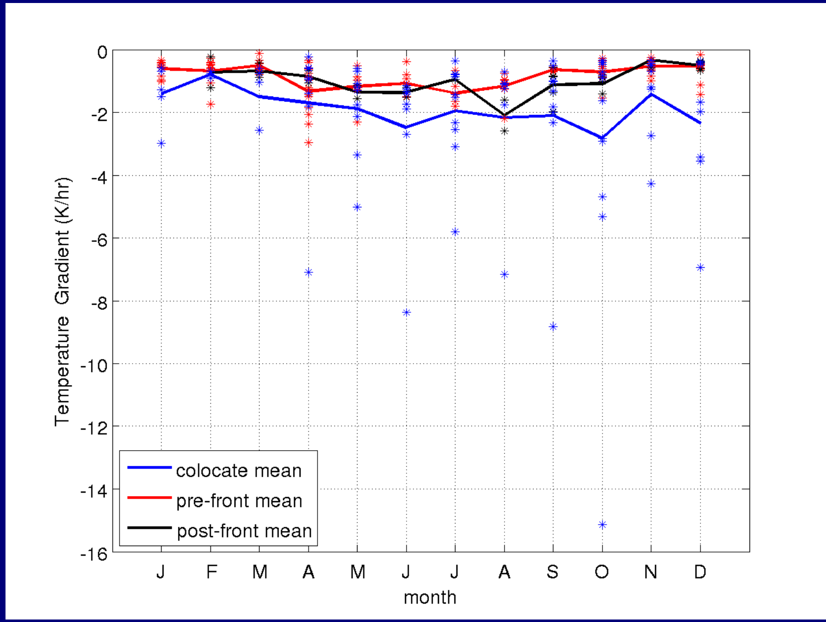
Precipitation as a function of temperature change





- The fronts with the strongest temperature change do not produce the most rain
- The most rain is associated with fronts with small temperature changes – potentially those fronts approaching occlusion

Location of wind shift



$$T_{gradient} = \frac{T(start) - T(end)}{time(start) - time(end)}$$

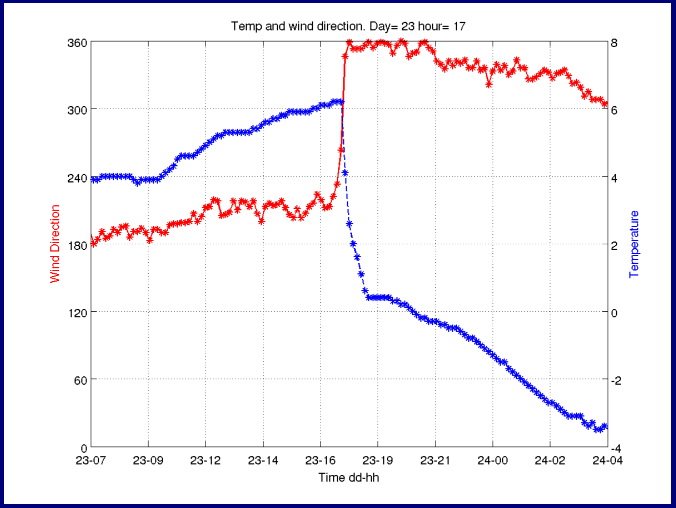
- The location of the wind shift (prefrontal, co-located etc.) does not determine the absolute temperature decrease
- The location of the wind shift effects the temperature gradient.
- All cold fronts with a strong temperature gradient had a co-located wind shift.
- Convergence leads to frontogenesis and strengthens the front

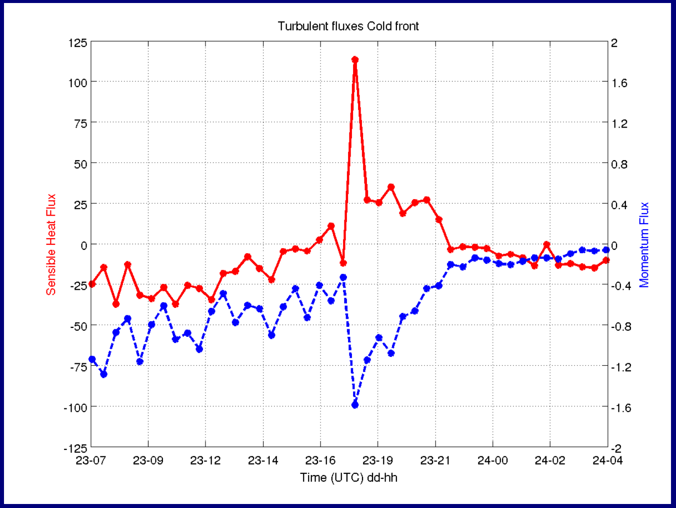
How do fronts affect boundary layer variables and what is the turbulent structure of frontal zones?

<u>Motivation:</u> What physical mechanism counteracts the intensification of temperature and velocity gradients across a developing front?

Do fronts obtain an equilibrium cross-front length scale when frontogenesis is balanced by turbulent mixing and dissipation?

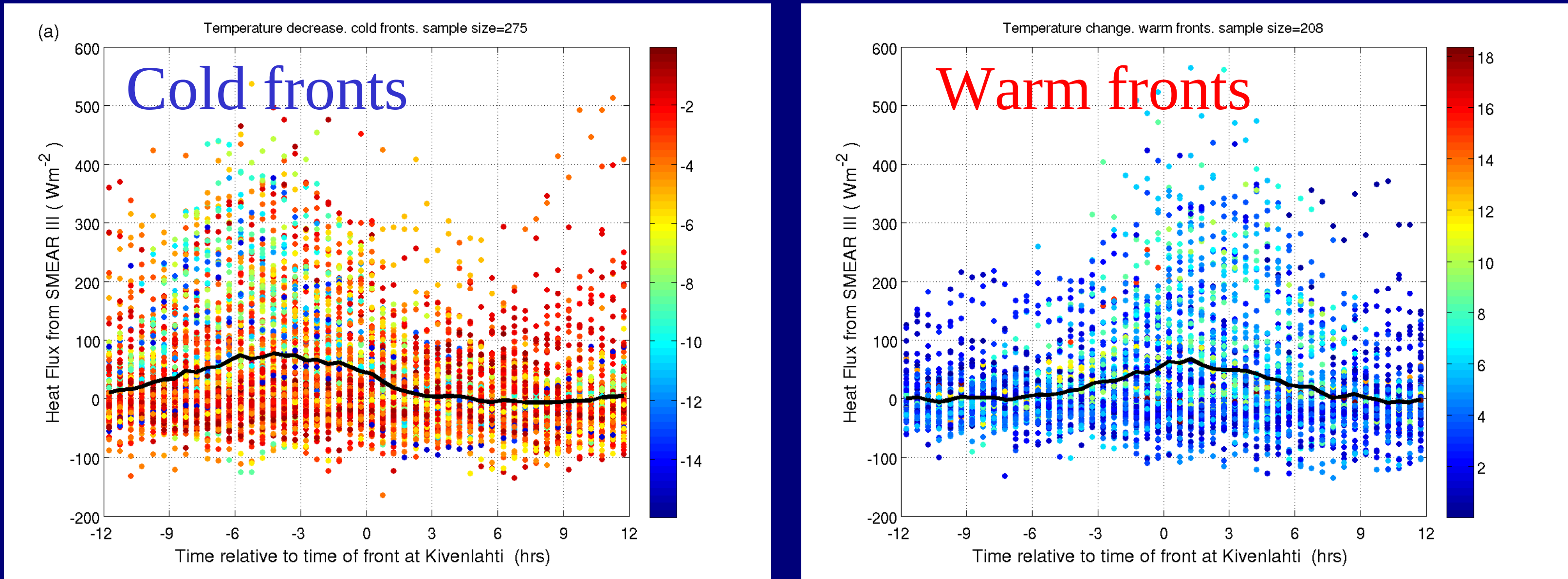
Effect of fronts on heat and momentum fluxes – an example





- Example of a sharp cold front
- Observed at 18 UTC
- Heat flux increased rapidly – the front modified the BL structure from weakly stable to unstable
- Magnitude of the momentum flux increases.
- However, not all fronts have such clear signals
- Missing flux data is common in fronts as eddy covariance technique assumes homogenous conditions.

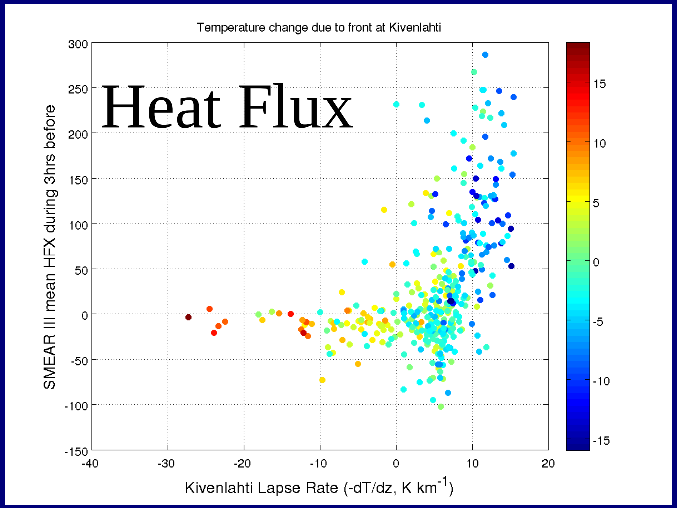
Average front: heat fluxes

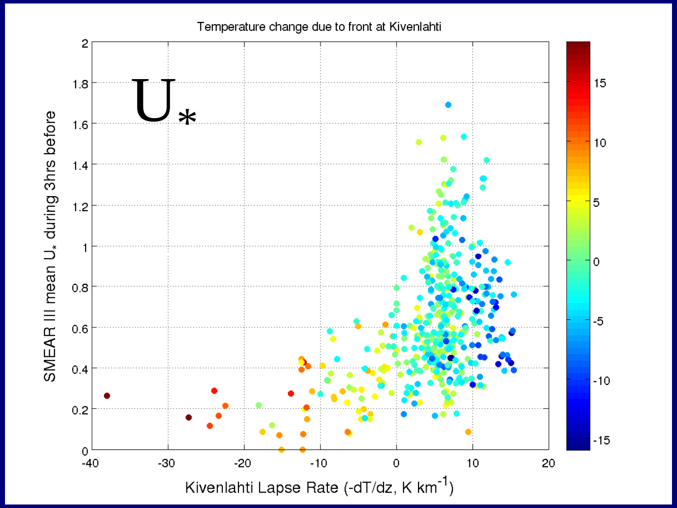


Colours indicate the temperature change due to each front

- Heat fluxes decrease after cold fronts
  - Likely strongly contaminated by the diurnal cycle.
- Heat fluxes also decrease slightly after warm front
- Too much variability for mean flux to be useful

How does the lapse rate affect BL variables?





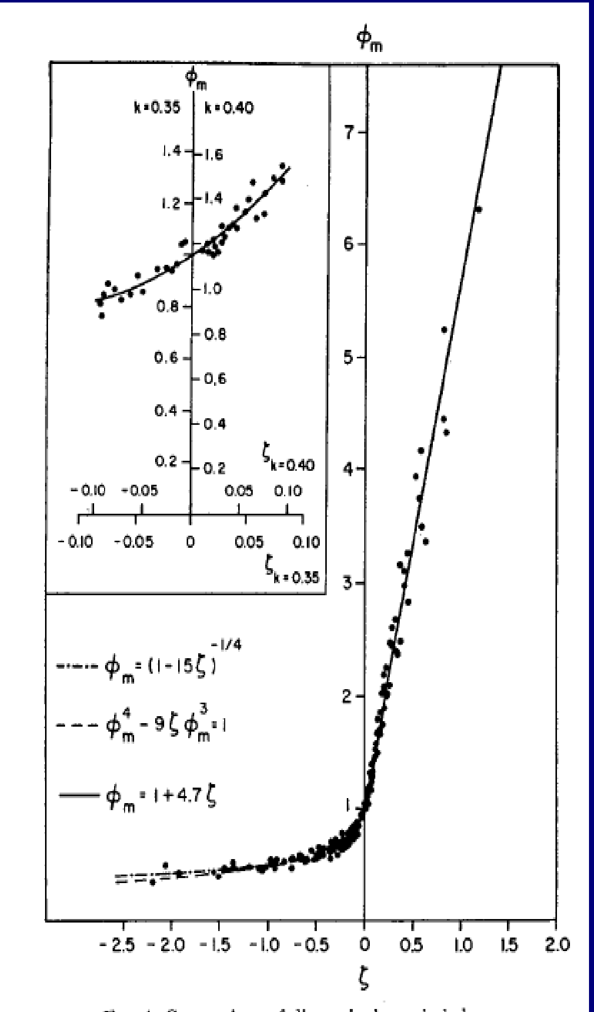


FIG. 1. Comparison of dimensionless wind shear observations with interpolation formulas.

Colours indicate the temperature change due to each front. Warm and cold fronts are on the same plots

Turbulence in frontal zones

- Turbulent Kinetic Energy (TKE) is the amount of kinetic energy due to turbulent eddies.
  - Can be produced by buoyancy or shear
  - In fronts, shear is strong so high TKE values can be expected
  - A large amount of turbulence prevents horizontal gradient of temperature become discontinuities
- Turbulent dissipation rate is the rate at which TKE is destroyed / converted to heat energy by viscous forces
  - Near the surface, shear production is balanced by dissipation
- Previous work on the frontal width problem (Blumen and Piper, 1999)
  - linear relationship between dissipation rate and frontal width

Turbulent dissipation rate (ϵ) in fronts

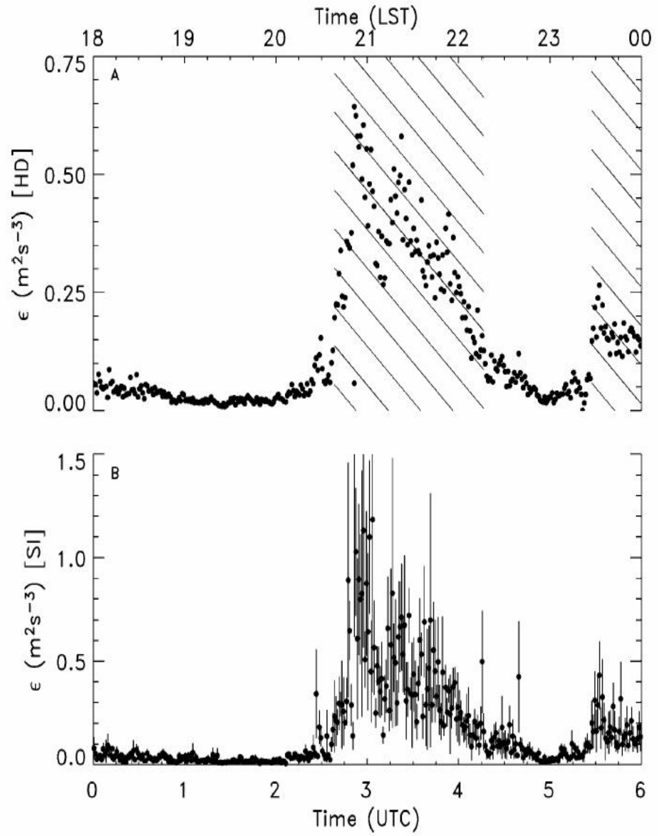
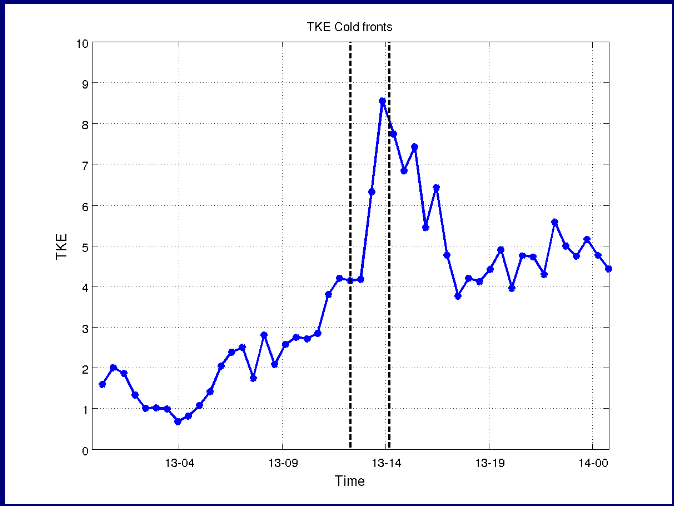


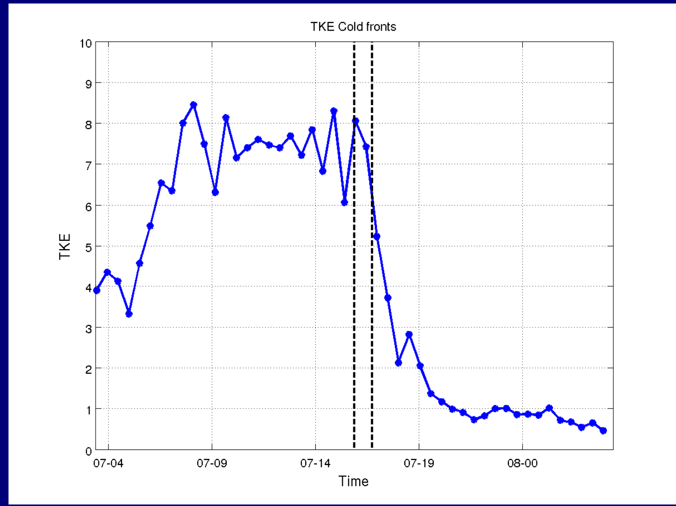
FIG. 6. Dissipation rate calculations from the 3-m hot-wire and sonic anemometers for the 20 Mar 1995 front. Values of ϵ are calculated in 60-s intervals. Error bars denote 95% confidence intervals on the means. (a) Direct dissipation technique from the hot wire (HD). Note the expanded ordinate. The error bars are smaller than the plot symbols. The hatched areas indicate when $U > 7$ m s^{-1}. (b) Inertial dissipation technique from the sonic (SI).

- Piper and Lundquist (2004) considered observations of dissipation in a frontal zone.
- Very little is known about turbulence within fronts, especially at dissipative scales
- SMEAR III data provides an ideal opportunity to investigate further – ongoing work with Leena Järvi

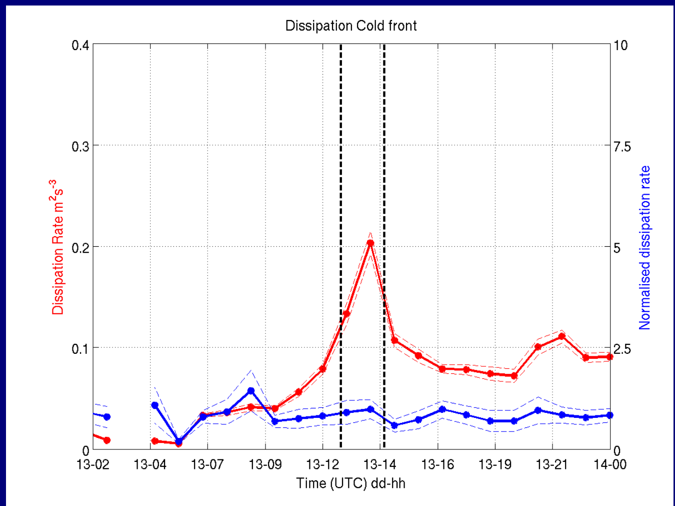
TKE and Dissipation rate in 2 cold fronts

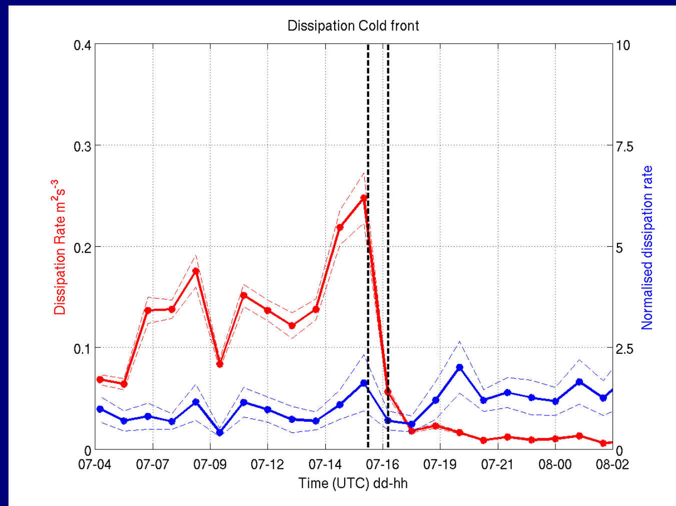
TKE





ε





Dashed lines show frontal zones

Conclusions

- A front is observed in Helsinki every 2.6 days.
- Cold fronts are most common; warm fronts the least common
- Seasonal and diurnal cycles exist

- Average temperature change due to cold fronts in -4.4C and +4.0C for warm fronts. Temperature change is largest at the surface
- Cold fronts have heavier, more localised rain than warm fronts
- Pre-frontal wind shifts are more common than co-located wind shifts
- Temperature change depends on direction that fronts approach from and the prefrontal lapse rate.

- Fronts can modify the boundary layer – sensible heat and momentum fluxes change as fronts pass.
- The heat and momentum fluxes are related to both temperature change and lapse rates
- Data exists to study turbulence and dissipation in frontal zones

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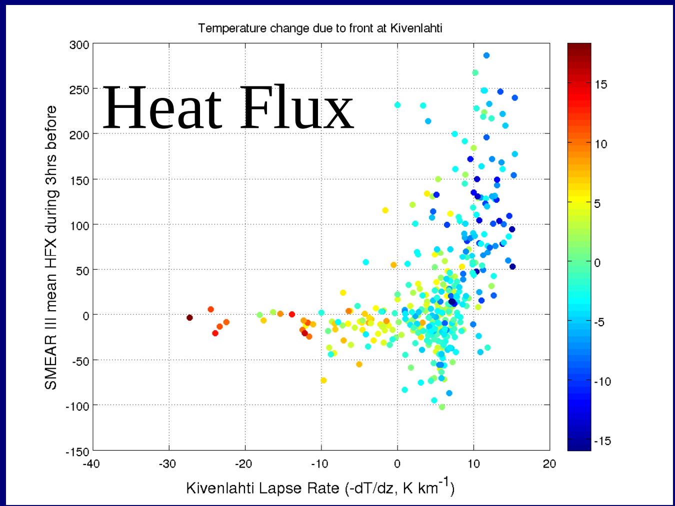
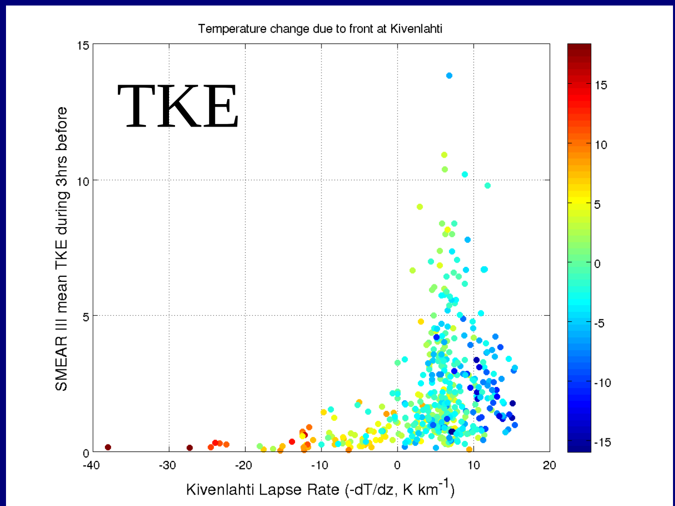
Data to analysis the mesoscale and microscale structure of fronts

- Climatology is enhanced by analysing observations of all 855 front.
- Kivenlahti Tower observations
  - Temperature at 7 heights (5, 26, 48, 93, 141, 218, 296 m)
  - Wind speed and direction at 4 levels (26, 93, 266, 327m)
- SMEAR III / Physicum roof data
  - Temperature
  - Dewpoint temperature
  - Precipitation
  - Wind speed and direction
  - Rain rate
  - Turbulent fluxes, TKE, Obukhov length and dissipation rate

How does the lapse rate affect BL variables?





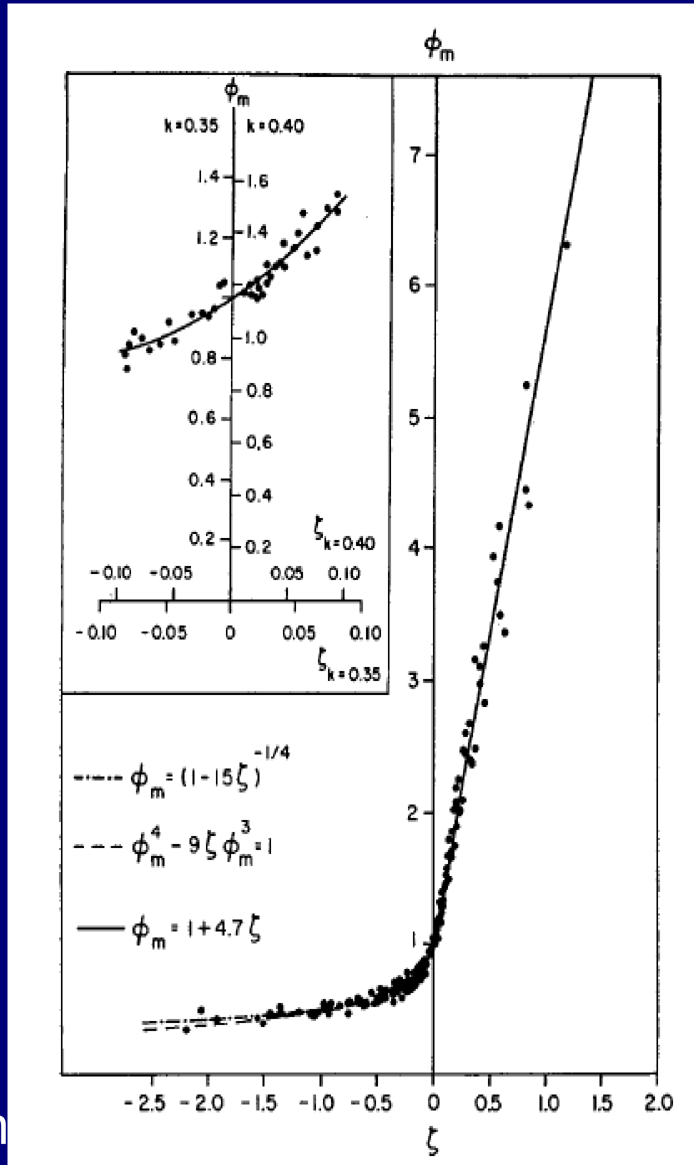
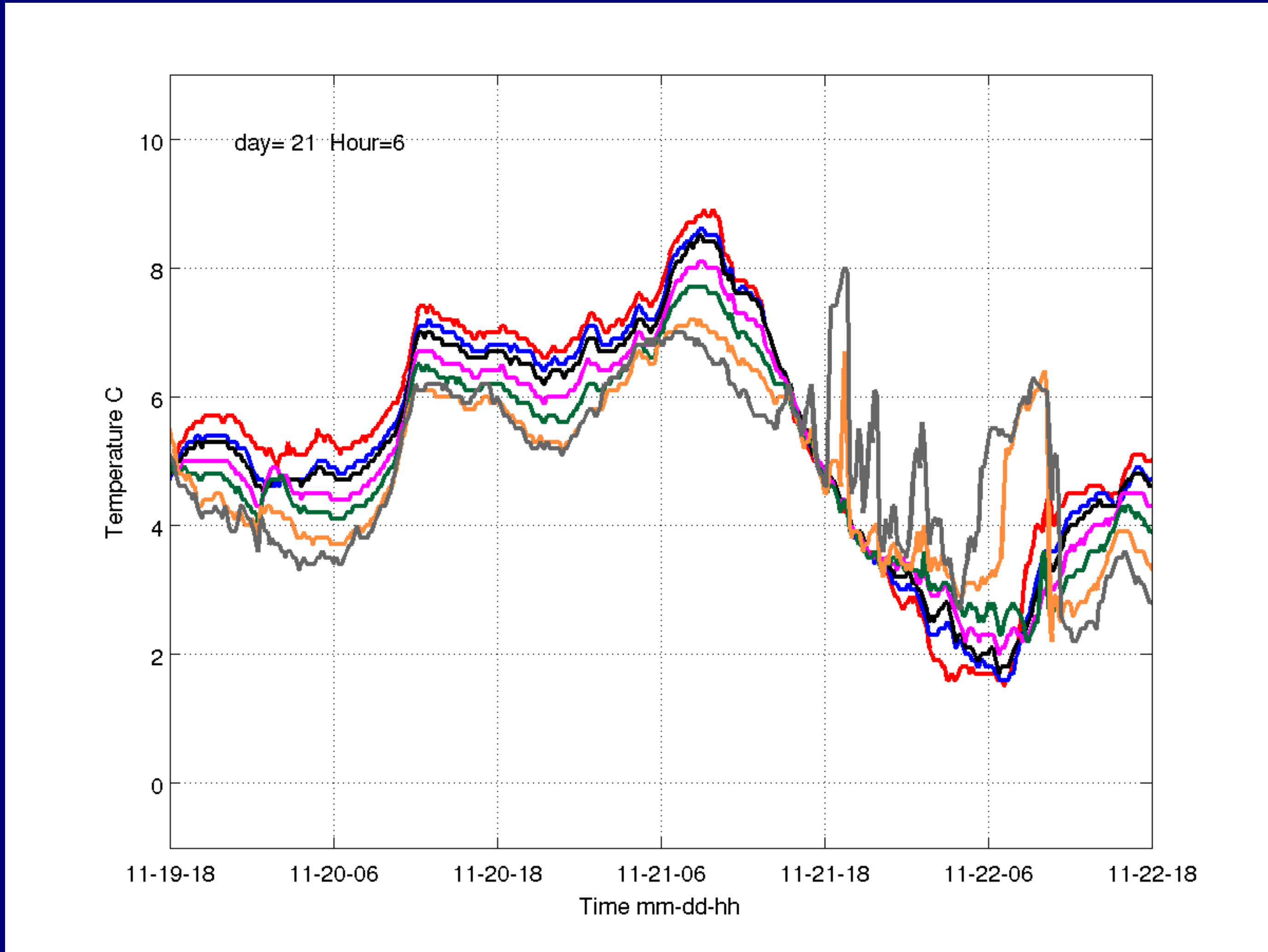


FIG. 1. Comparison of dimensionless wind shear observations with interpolation formulas.

Colours indicate the temperature ch… n

and cold fronts are or…

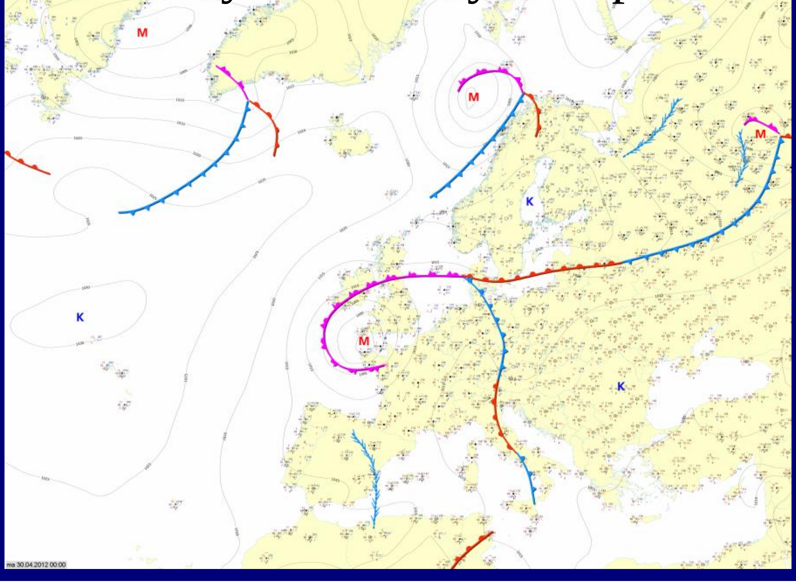
Many fronts have interesting structures



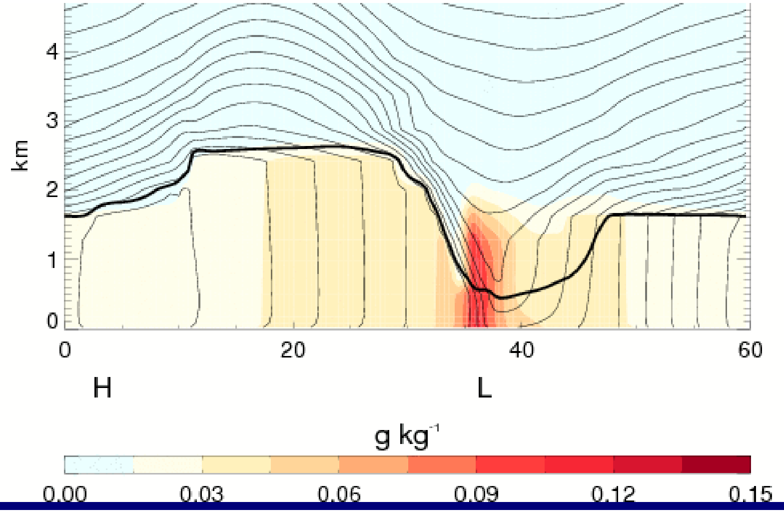
Why are fronts important?

- Critical in determining the weather in mid-latitudes
- Can cause hazardous weather
  - Strong winds, heavy snow, initiate convection
- Can ventilate pollutants out of the boundary layer
  - Can affect local air quality
- Can transport pollutants long distances.

FMI analysis Monday 30 April



Cold front and idealised pollutant



Turbulent dissipation rate (ϵ) in fronts

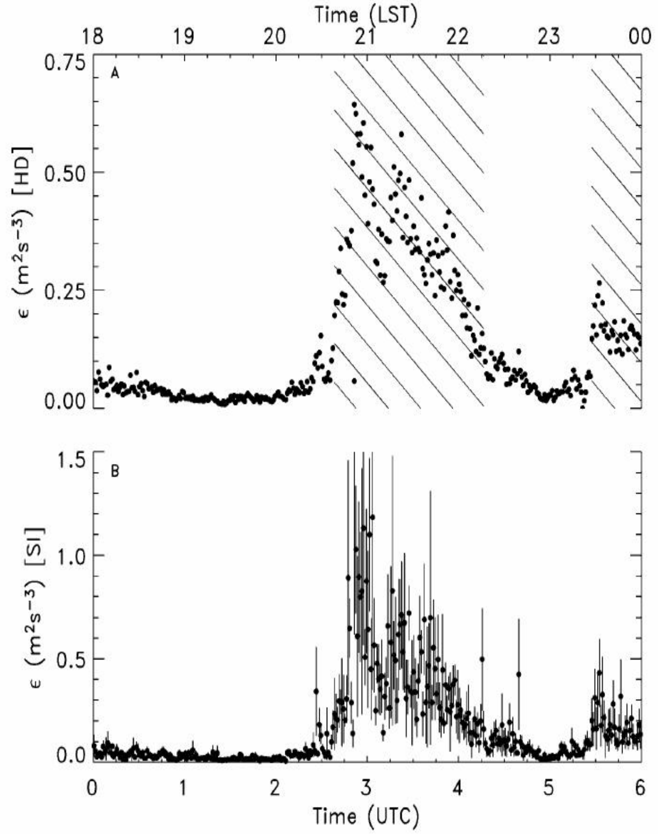


FIG. 6. Dissipation rate calculations from the 3-m hot-wire and sonic anemometers for the 20 Mar 1995 front. Values of ϵ are calculated in 60-s intervals. Error bars denote 95% confidence intervals on the means. (a) Direct dissipation technique from the hot wire (HD). Note the expanded ordinate. The error bars are smaller than the plot symbols. The hatched areas indicate when $U > 7$ m s^{-1}. (b) Inertial dissipation technique from the sonic (SI).

- Piper and Lundquist (2004) considered observations of dissipation in a frontal zone.
- Very little is known about turbulence within fronts, especially at dissipative scales

$$\epsilon = \frac{2\pi}{U}\left[\frac{f^{5/3}S_{u_i}(f)}{\alpha_i}\right]^{3/2}.$$

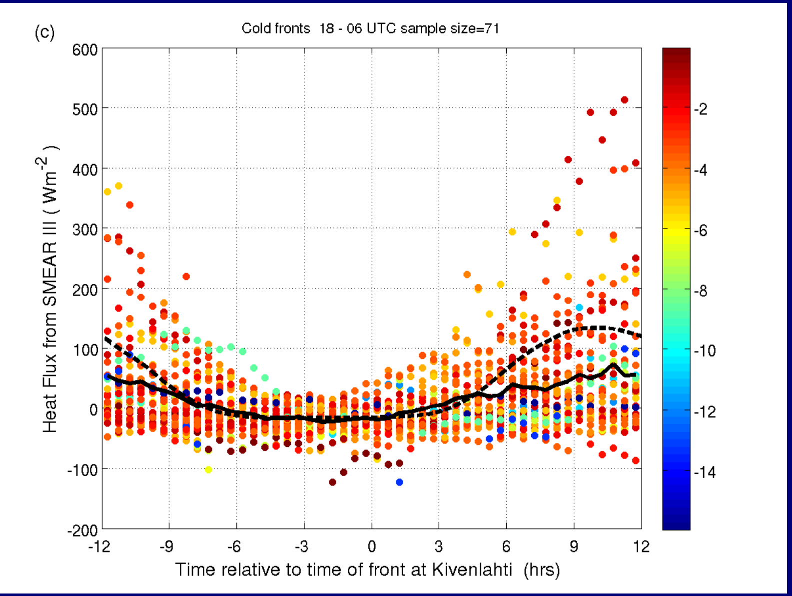
f = frequency

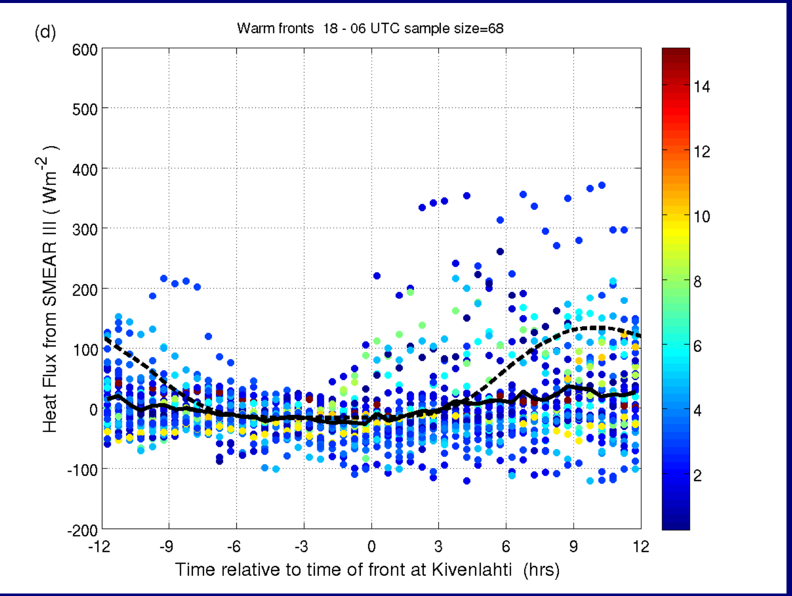
S_u = streamwise velocity spectra

U = mean wind speed

α = constant

Nocturnal fronts (18 UTC – 06 UTC)





Time difference between SWC and Kivenlahti observations

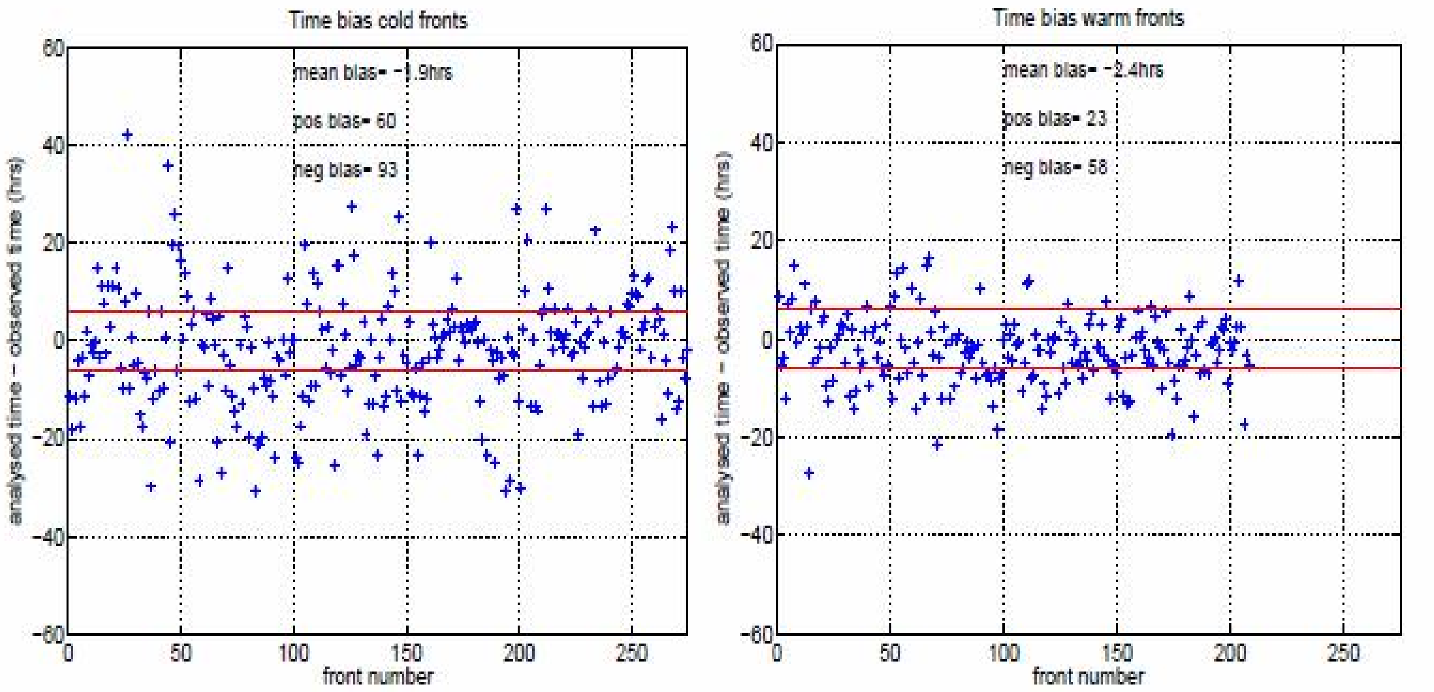
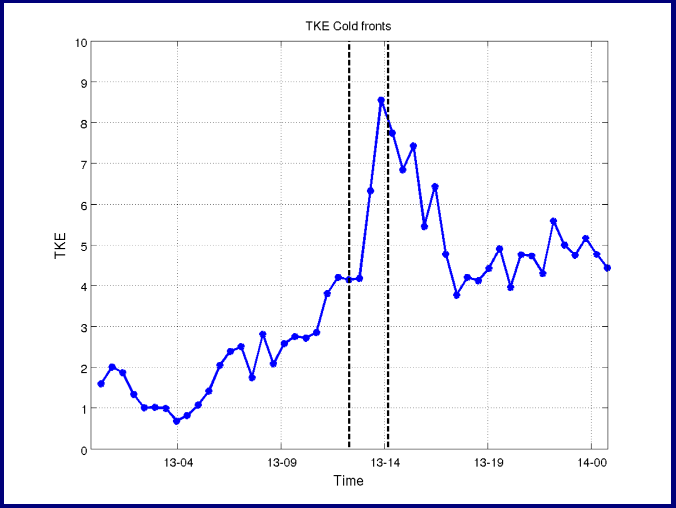
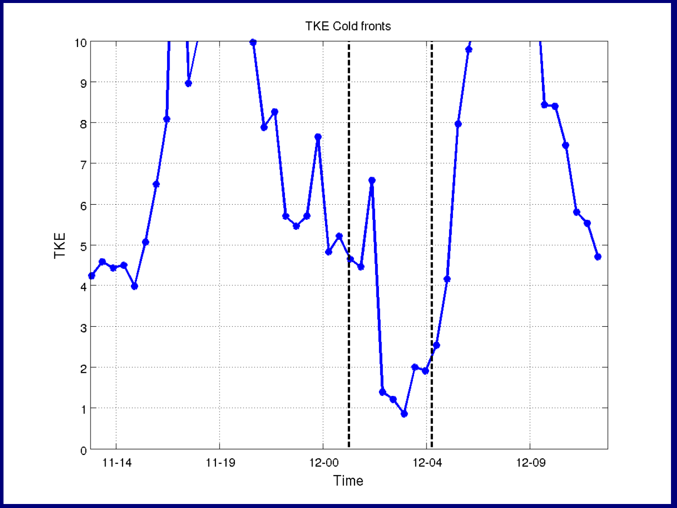
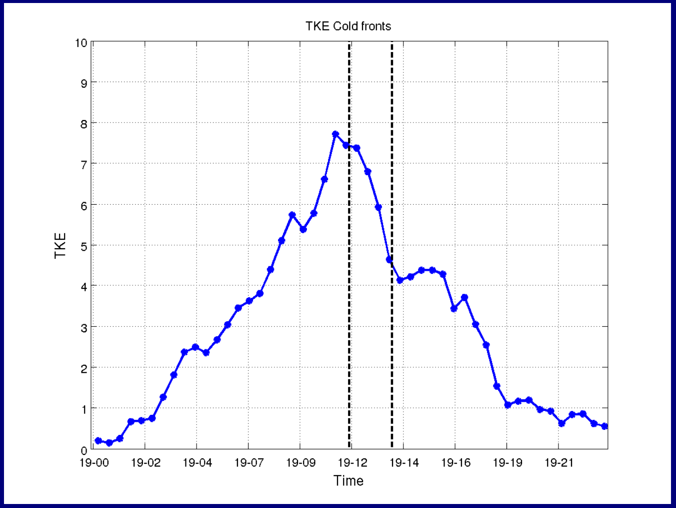


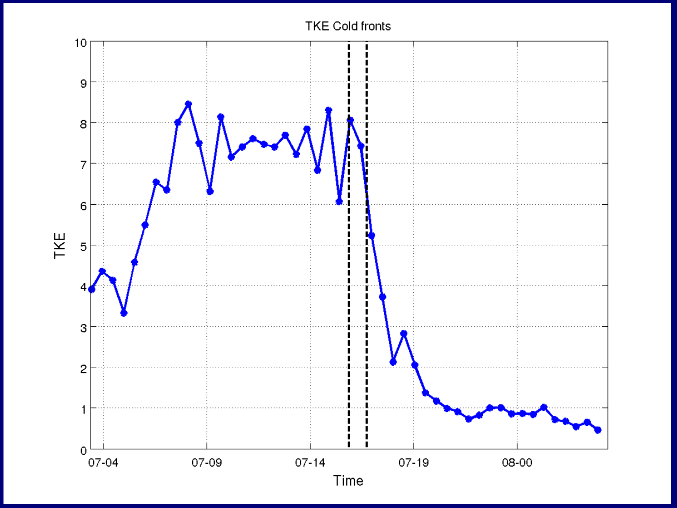
Figure 2. Time bias between SWC charts and Kivenlahti observations for cold fronts (left) and warm fronts (right)

TKE in cold fronts

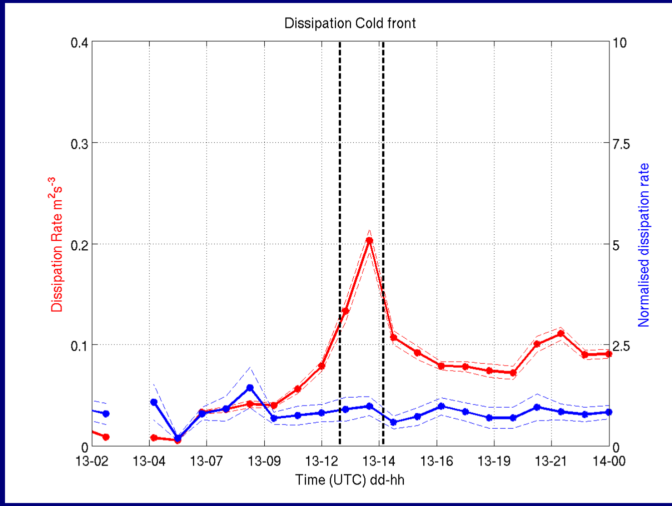


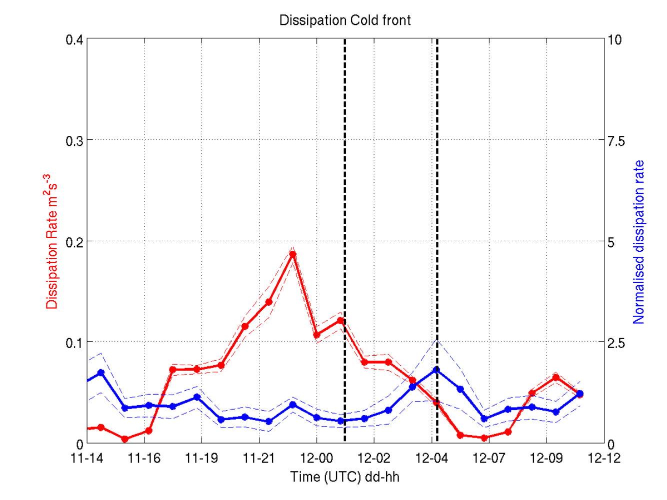


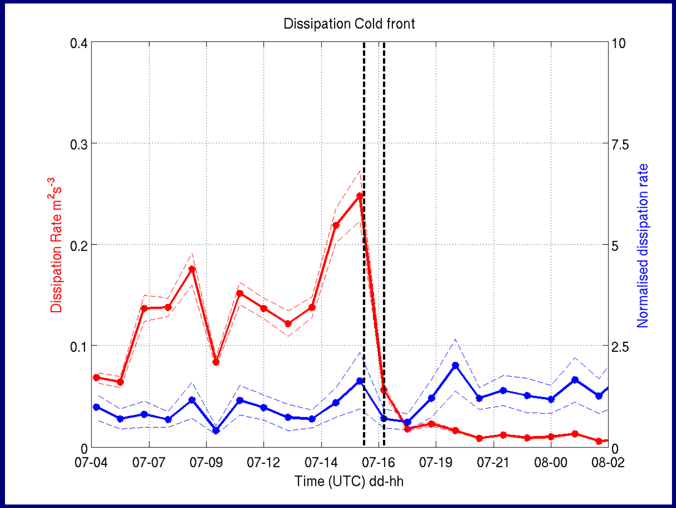


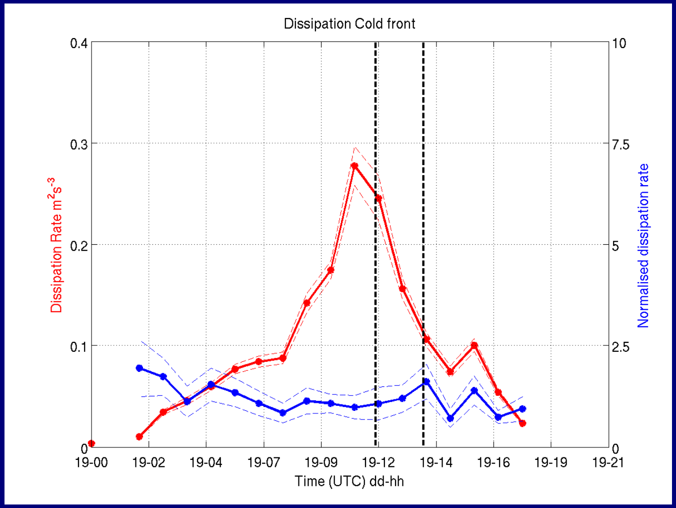


Examples of dissipation rates in cold fronts



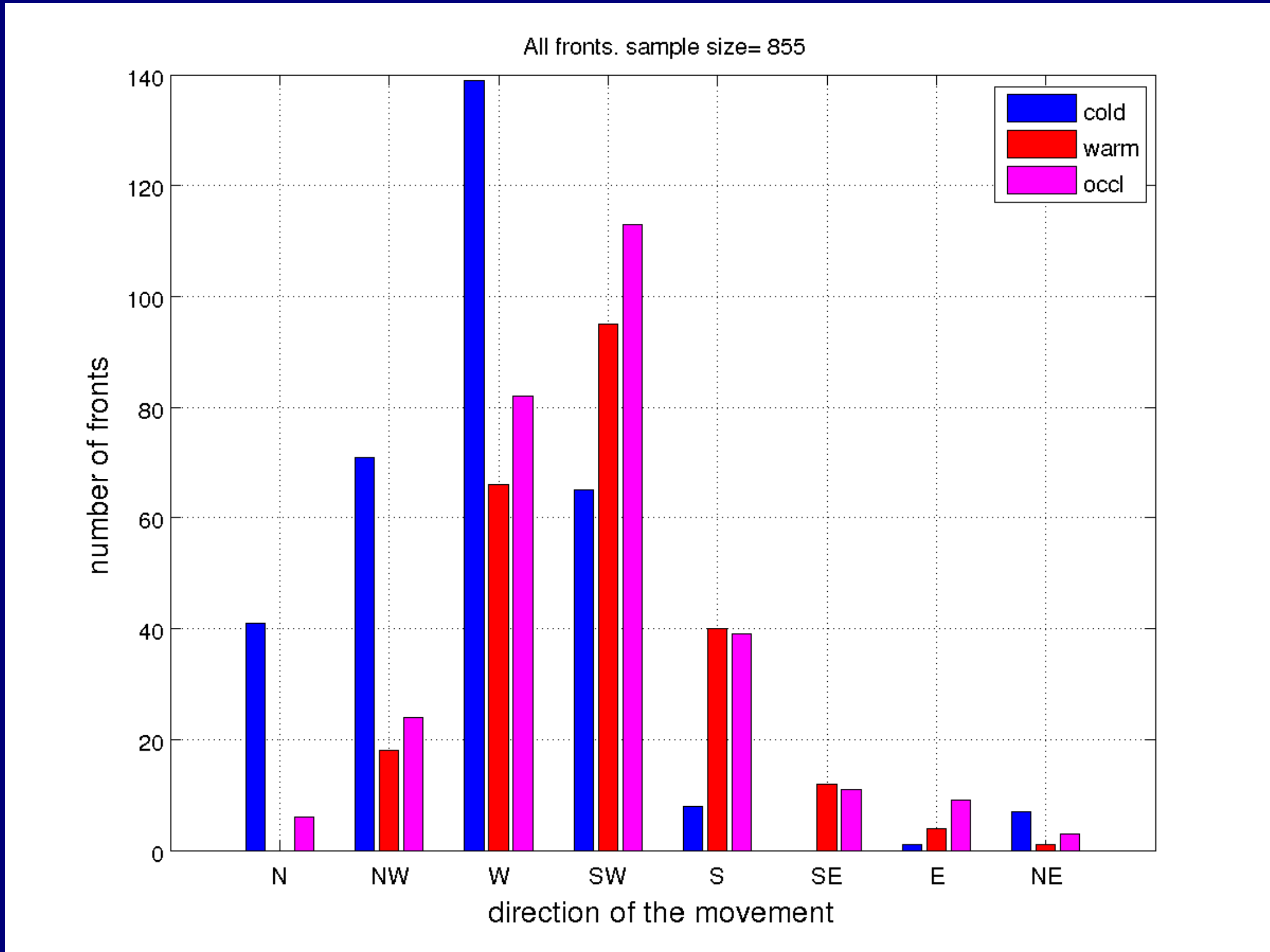






Dashed lines show frontal zones. Considerable variability

Direction that fronts approach Helsinki from



Factors controlling the tilt of fronts