

Improving forecasts via subspace projections

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Outline

- 1 Improving hierarchical forecasts
- 2 Improving univariate forecasts
- 3 Improving cross-temporal forecasts
- 4 Improving multivariate forecasts
- 5 Final comments

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1 Improving hierarchical forecasts

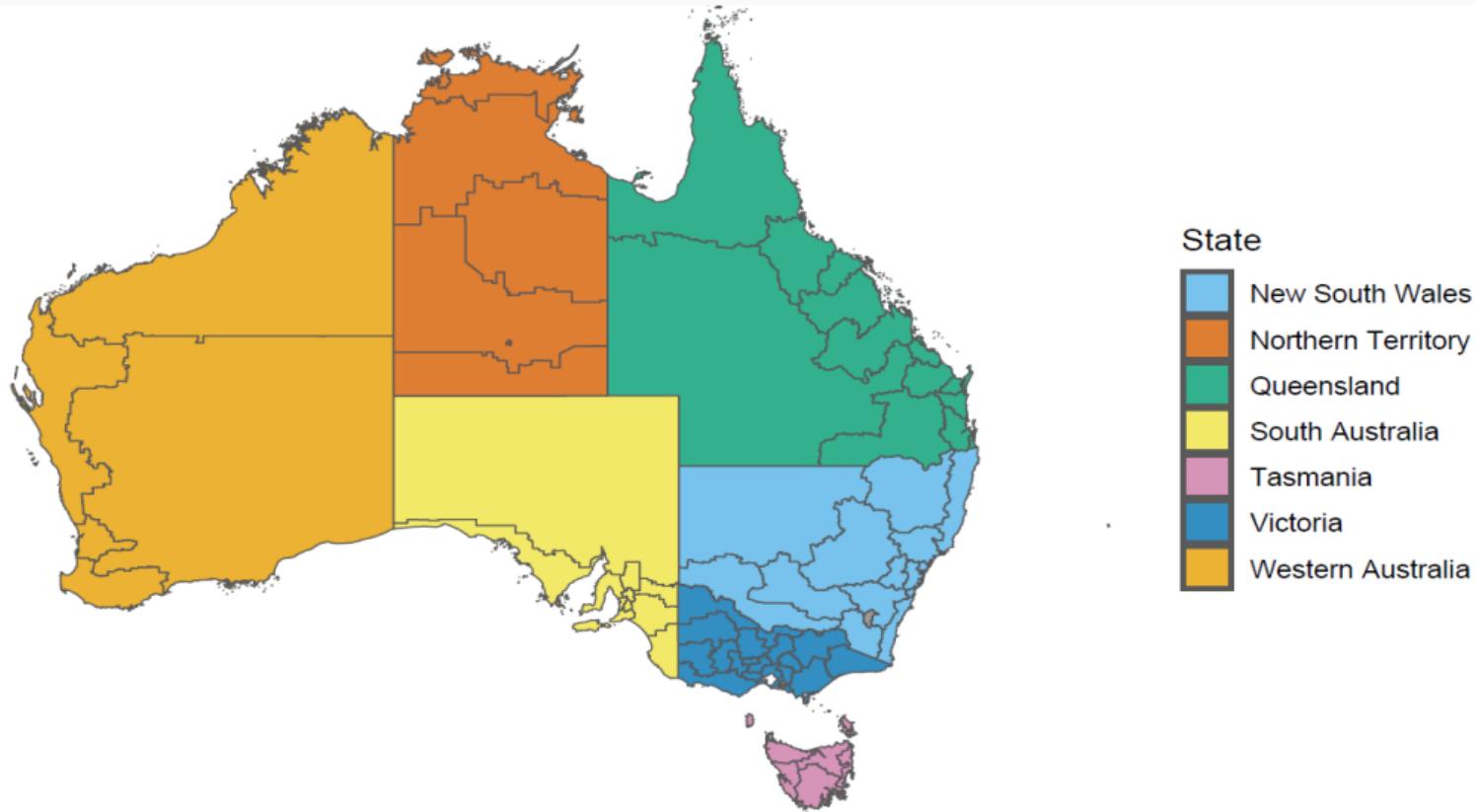
2 Improving univariate forecasts

3 Improving cross-temporal forecasts

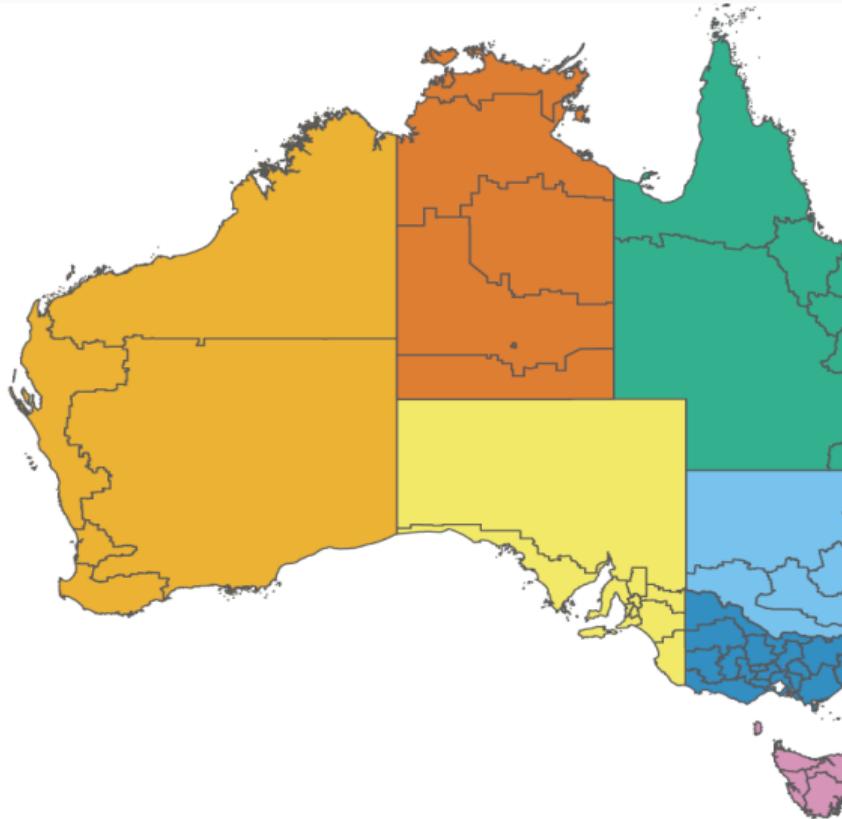
4 Improving multivariate forecasts

5 Final comments

Australian tourism regions



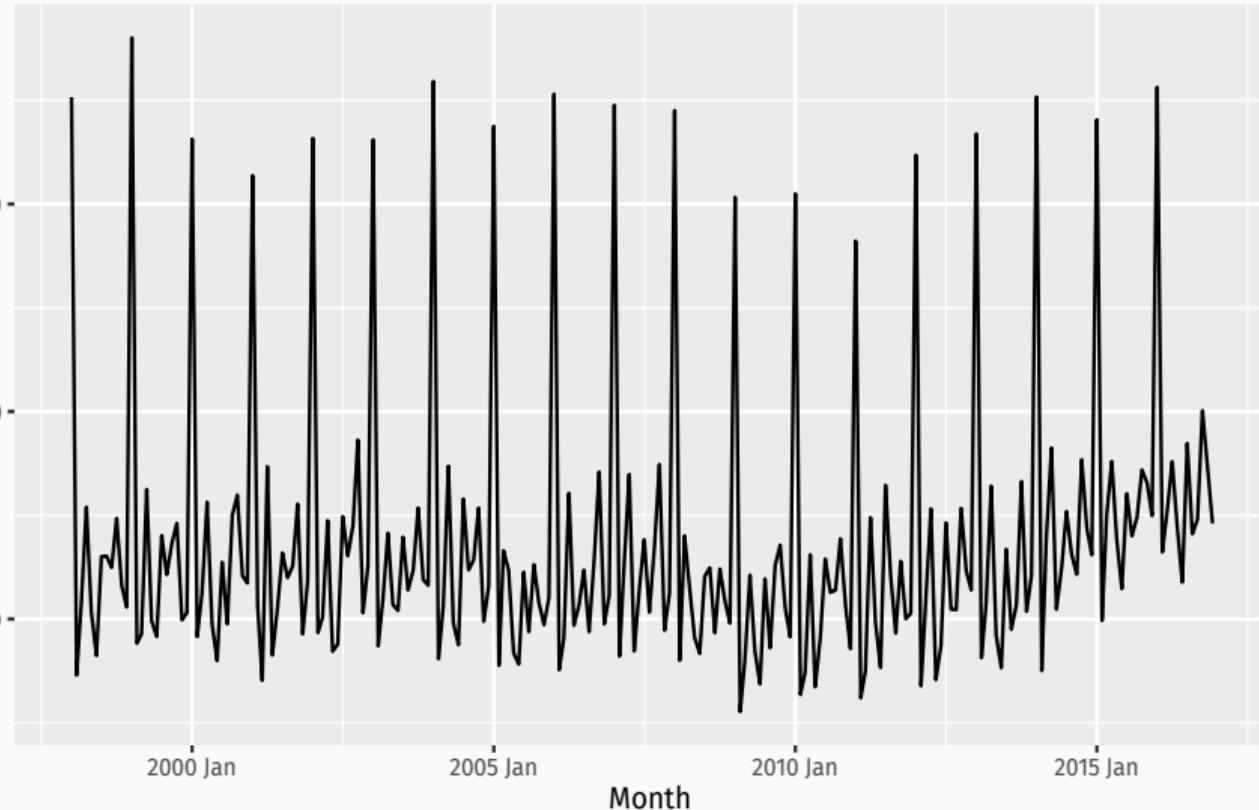
Australian tourism regions



- Monthly data on visitor night: 1998 – 2019
- From *National Visitor Survey*, annual interviews of 120,000 Australians aged 15+.
- Geographical hierarchy split by
 - ▶ 7 states
 - ▶ 27 zones
 - ▶ 75 regions

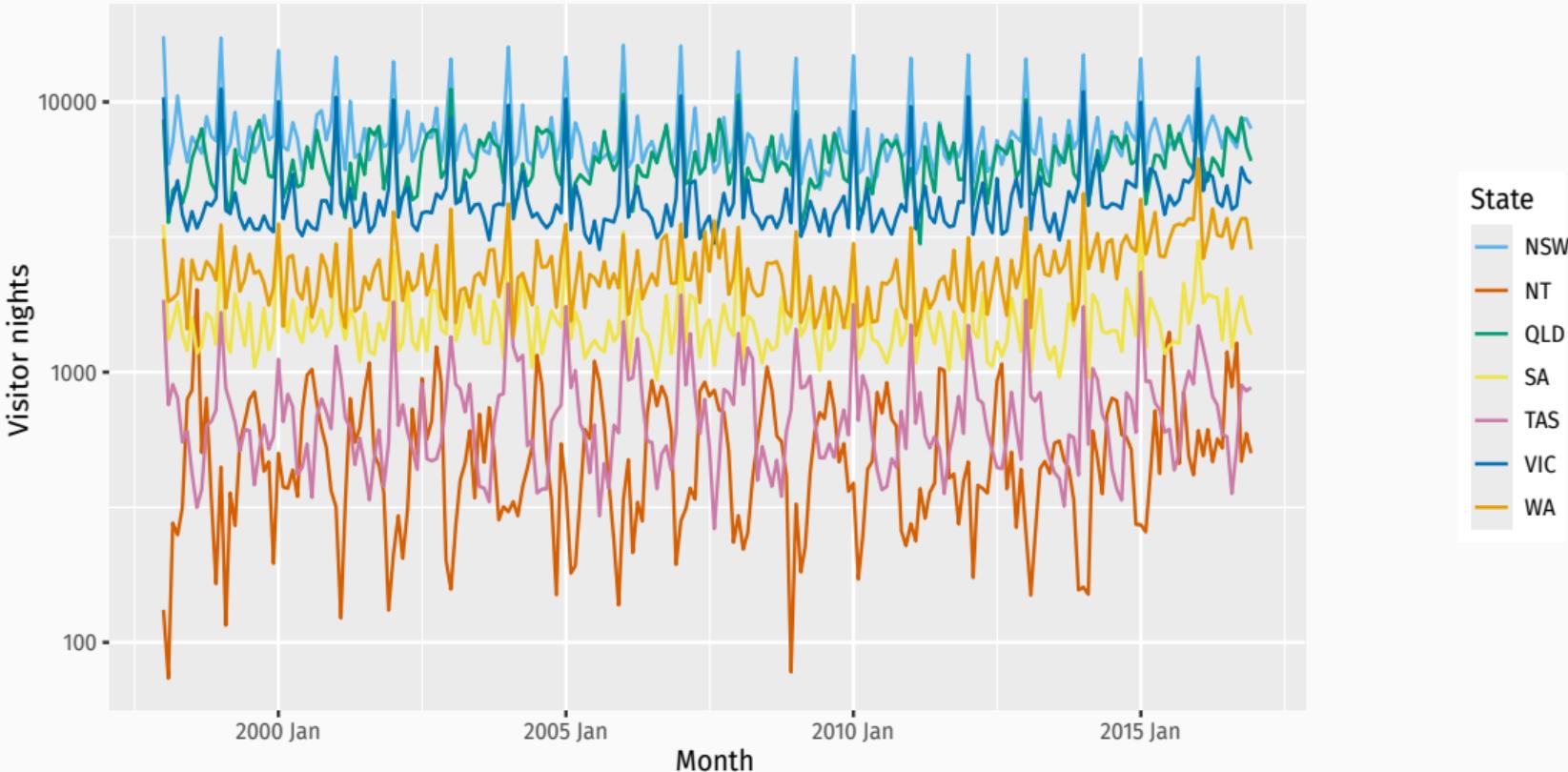
Australian tourism data

Total domestic travel: Australia



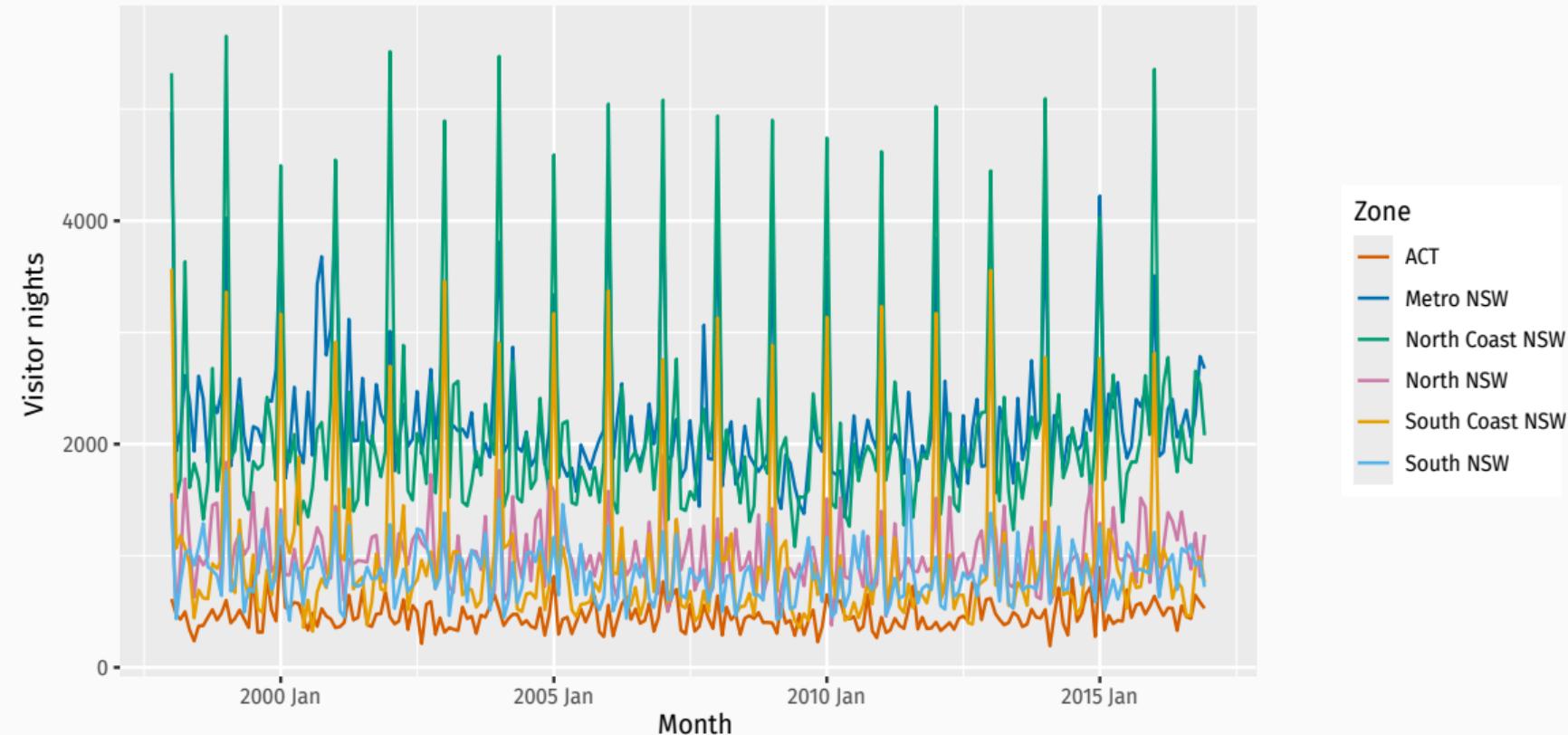
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Total domestic travel: by state



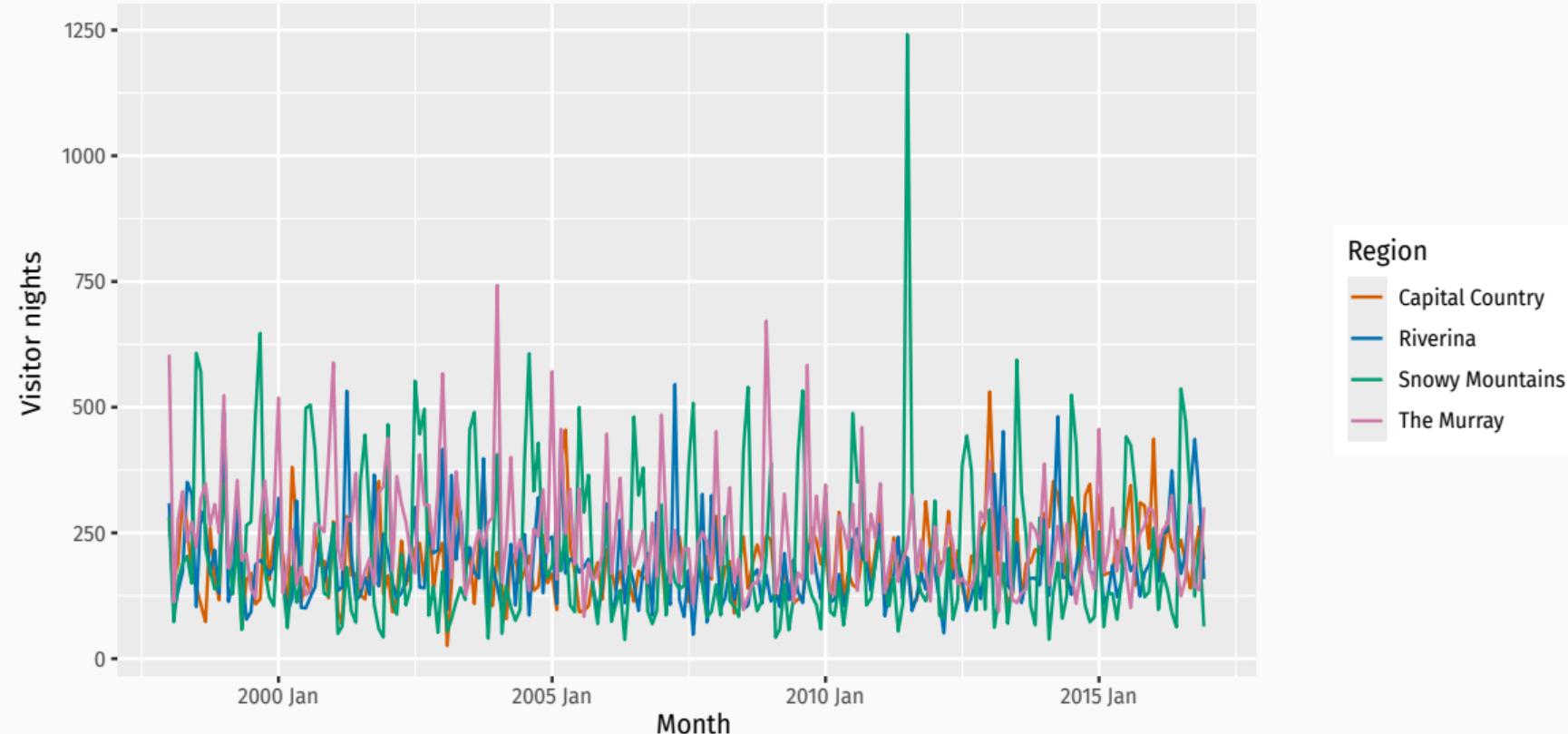
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Total domestic travel: NSW by zone



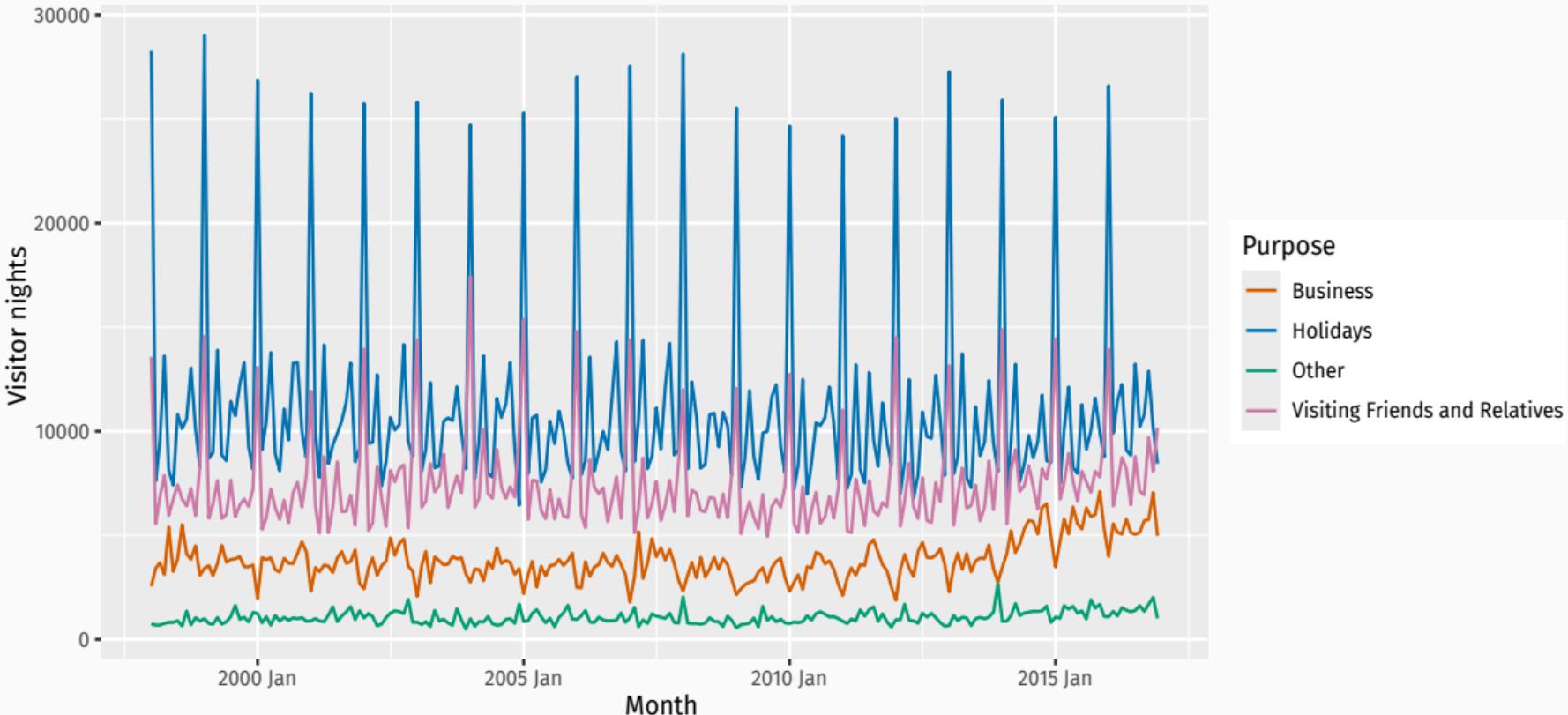
Australian tourism data

Total domestic travel: South NSW by region



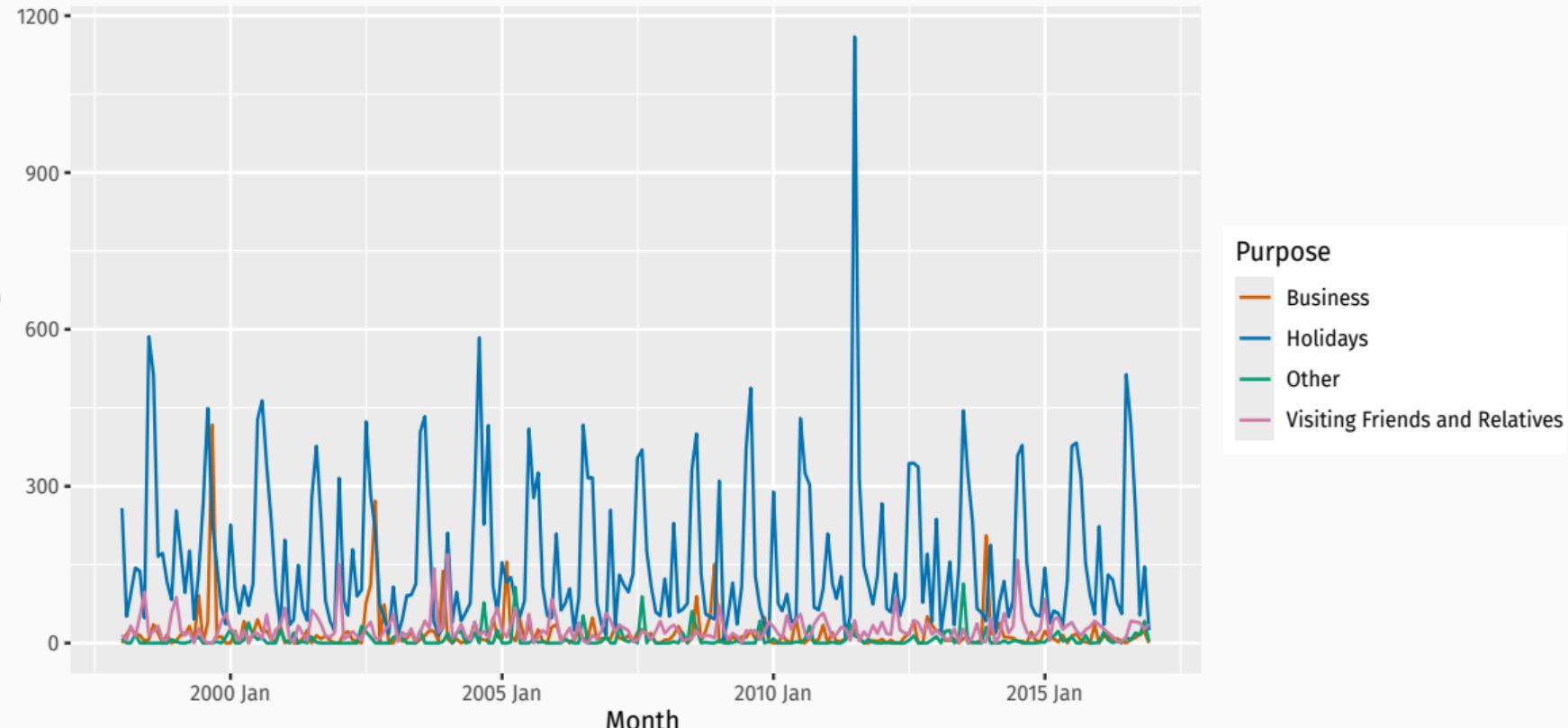
Australian tourism data

Total domestic travel: by purpose of travel



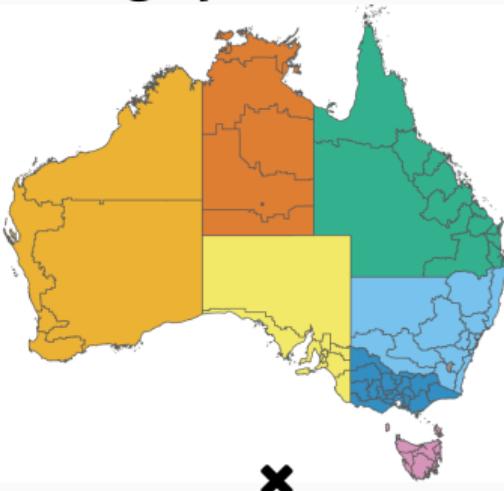
Australian tourism data

Total domestic travel: Snowy Mountains by purpose of travel



Australian tourism data

Geographical division



Purpose of travel

Holiday, Visiting friends & relatives, Business, Other

Grouped time series

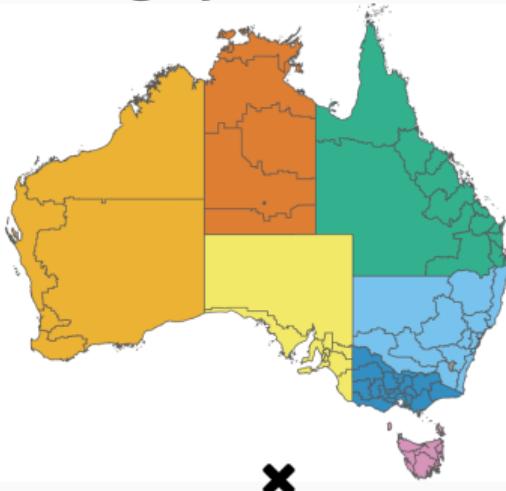
(geographical divisions × purpose of travel)

	AUS	States	Zones	Regions	Tot
geographical	1	7	21	76	105
purpose	4	28	84	304	420
total	5	35	105	380	525

m = 304 and n = 525

Australian tourism data

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- Need forecasts at all levels of aggregation.
- Forecasts generated by different agents/models will not adhere to aggregation constraints.

Key idea

- Traditional single level approaches: bottom-up, top-down or middle-out.

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G Athanasopoulos, R Ahmed, and R Hyndman (2009). “**Hierarchical forecasts for Australian domestic tourism**”. In: *International Journal of Forecasting* 25, pp. 146–166. URL: <https://doi.org/10.1016/j.ijforecast.2008.07.004>



RJ Hyndman, R Ahmed, G Athanasopoulos, and H Shang (2011). “**Optimal combination forecasts for hierarchical time series**”. In: *Computational Statistics & Data Analysis* 55.9, pp. 2579–2589. URL: <https://doi.org/10.1016/j.csda.2011.03.006>

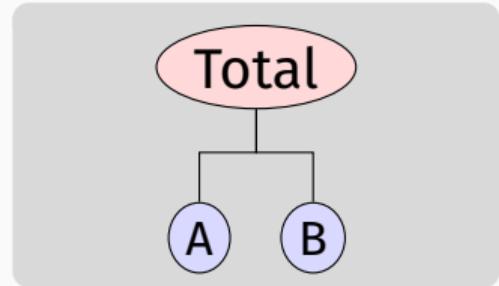


RJ Hyndman and G Athanasopoulos (2021). **Forecasting: principles and practice**. 3rd Edn. Melbourne, Australia. URL: <http://otexts.com/fpp3/>

Notation

$$\mathbf{y}_t = \mathbf{S}\mathbf{b}_t$$

- \mathbf{y}_t = vector of all series at time t
- \mathbf{b}_t = vector of most disaggregated series at time t
- \mathbf{S} = “structural matrix” containing the linear constraints.

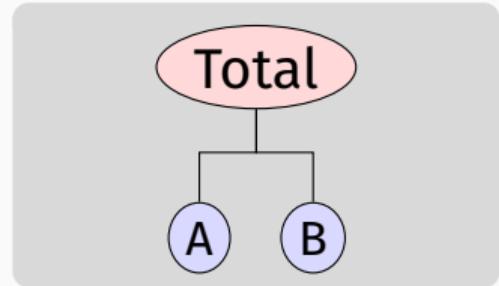


$$\begin{aligned}\mathbf{y}_t &= \begin{pmatrix} y_{\text{Total},t} \\ y_{A,t} \\ y_{B,t} \end{pmatrix} \\ &= \underbrace{\begin{pmatrix} 1 & 1 \\ 1 & 0 \\ 0 & 1 \end{pmatrix}}_S \underbrace{\begin{pmatrix} y_{A,t} \\ y_{B,t} \end{pmatrix}}_{\mathbf{b}_t}\end{aligned}$$

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- m – number of bottom-level series
- n – number of all series



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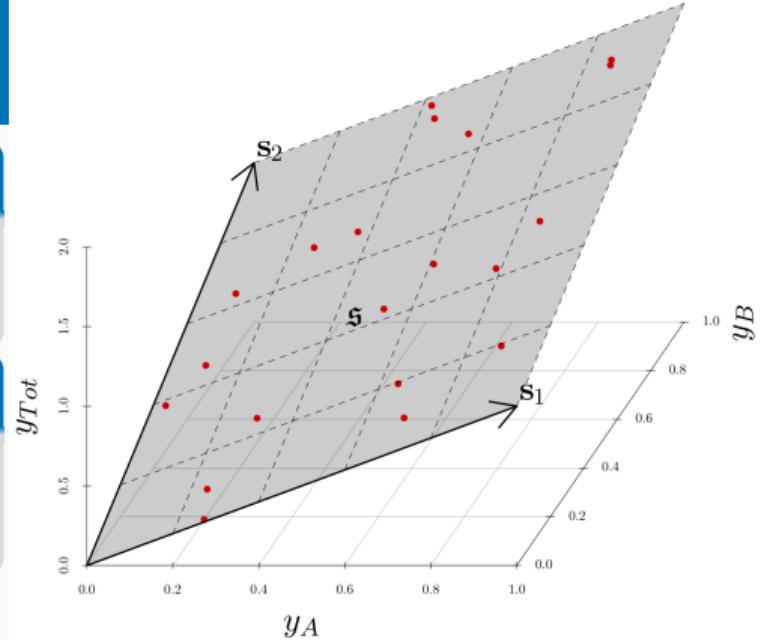
The coherent subspace

Hierarchical time series

Multivariate time series $\mathbf{y}_t \in \mathbb{R}^n$, bound by linear constraints.

Coherent subspace

m -dimensional linear subspace $\mathfrak{s} \subset \mathbb{R}^n$ for which linear constraints hold for all $\mathbf{y}_t \in \mathfrak{s}$.



$$y_{Tot} = y_A + y_B$$

The coherent subspace

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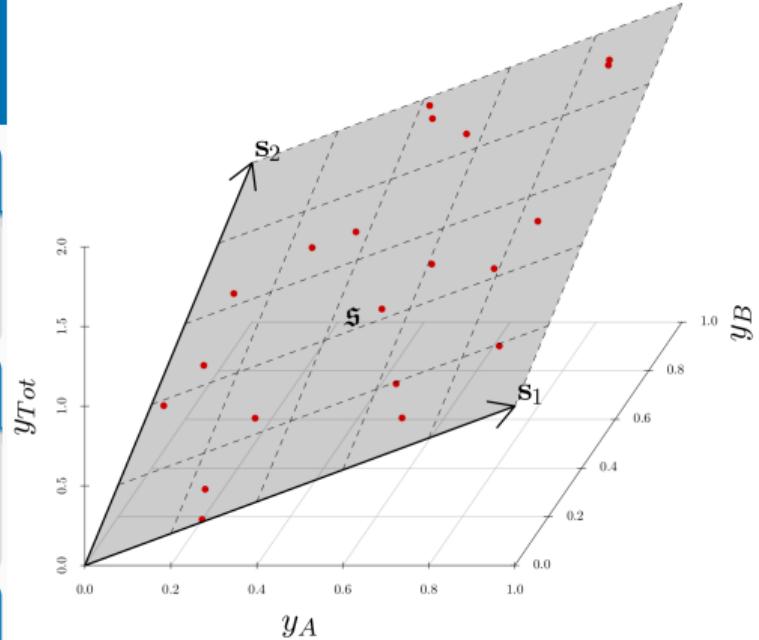
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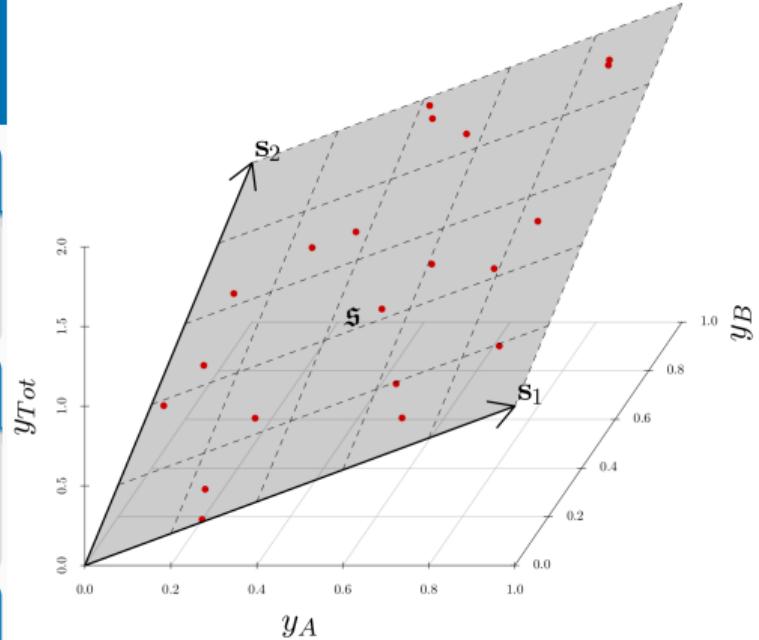
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Base forecasts

Let $\hat{\mathbf{y}}_{T+h|T}$ be vector of *incoherent* initial h -step forecasts.



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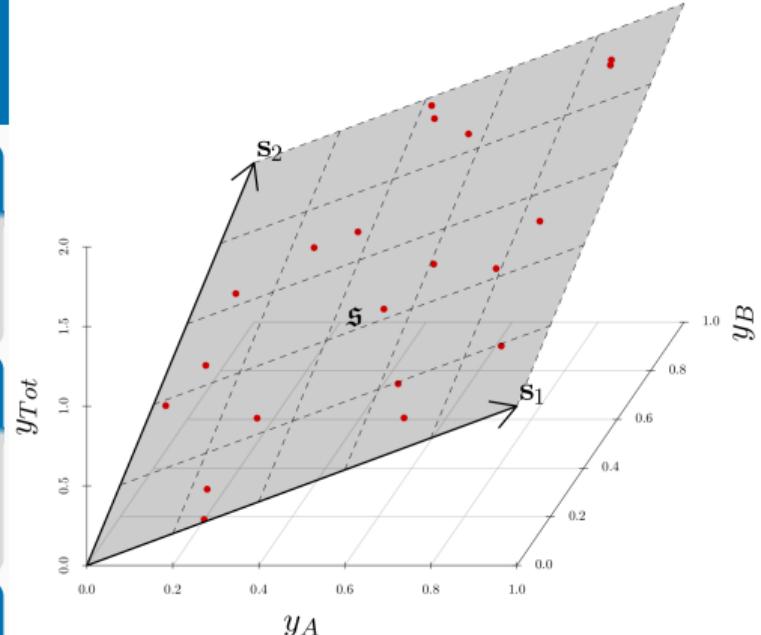
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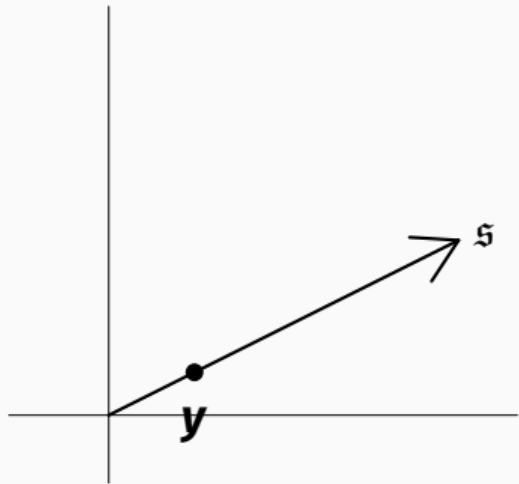
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Reconciled forecasts

Let \mathbf{SG} be a projection matrix.

$\tilde{\mathbf{y}}_{T+h|T} = \mathbf{SG}\hat{\mathbf{y}}_{T+h|T}$ “reconciles” $\hat{\mathbf{y}}_{T+h|T}$.

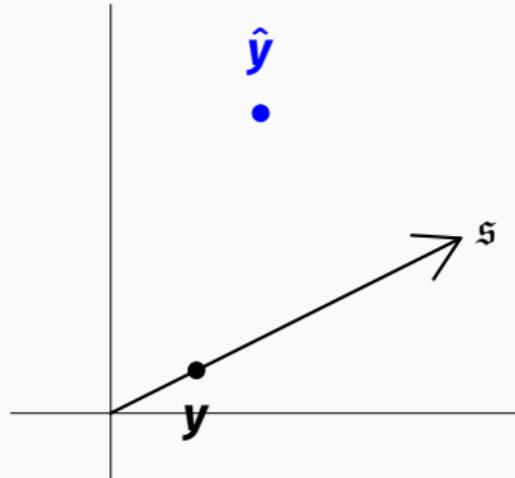
Geometry of forecast reconciliation



Geometry of forecast reconciliation

Reconciled point forecasts

Let ψ be a mapping, $\psi : \mathbb{R}^n \rightarrow \mathfrak{s}$. The point forecast $\tilde{\mathbf{y}}_{T+h|T} = \psi(\hat{\mathbf{y}}_{T+h|T})$ “reconciles” a base forecast $\hat{\mathbf{y}}_{T+h|T}$ with respect to the mapping $\psi(.)$



Geometry of forecast reconciliation

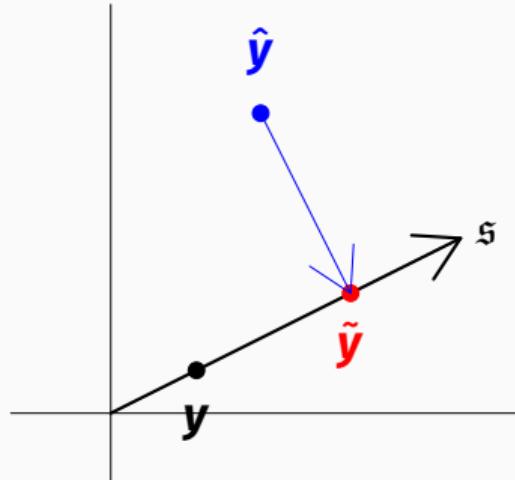
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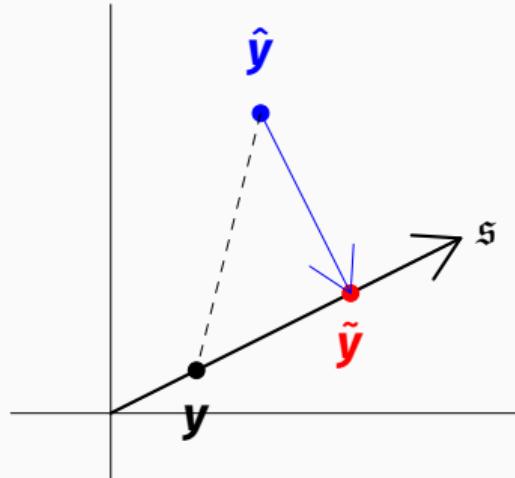
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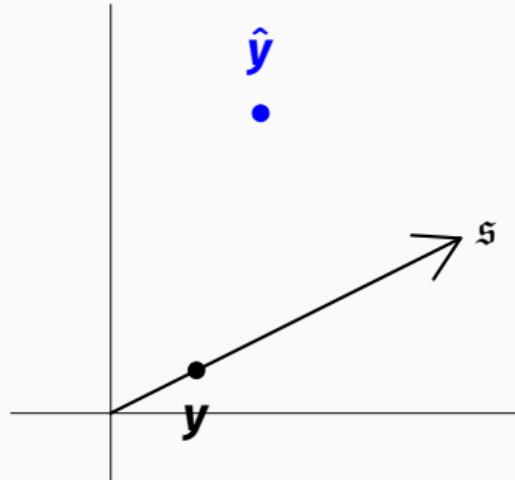
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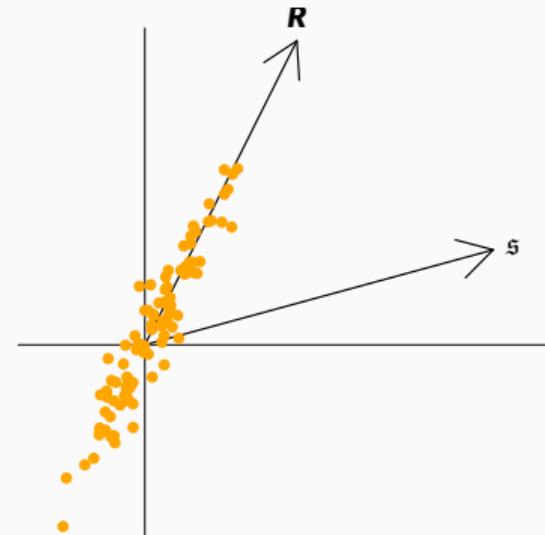
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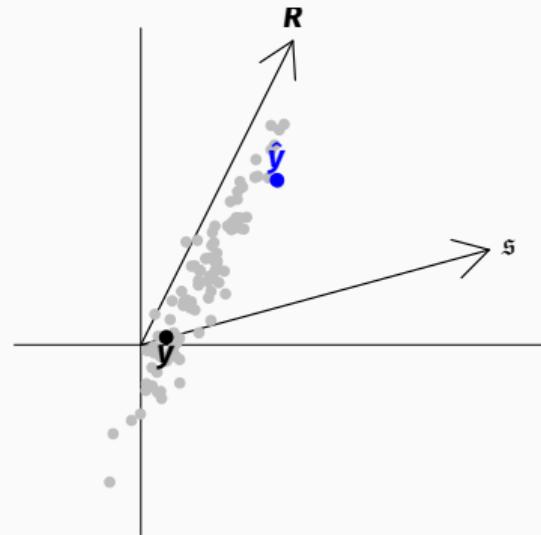
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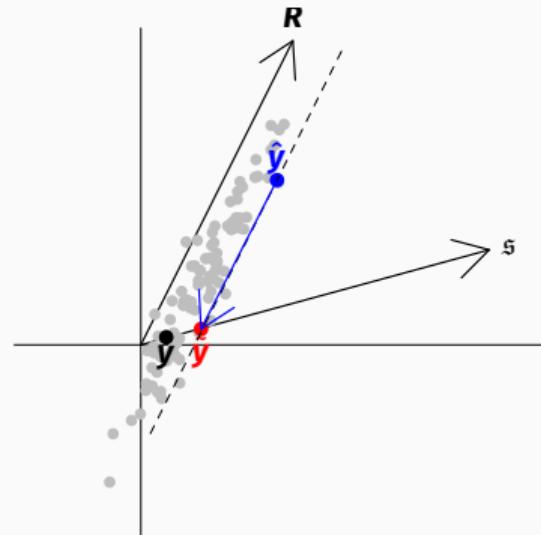
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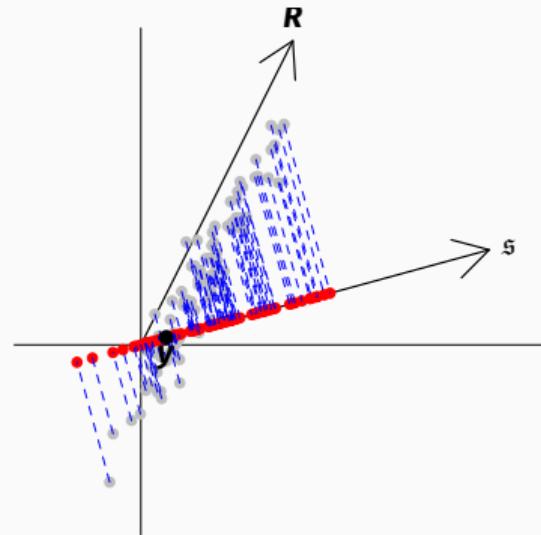
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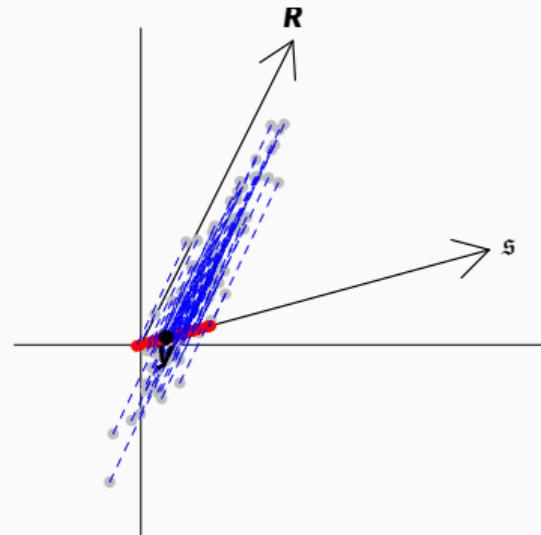
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- Let $\mathbf{W}_h = \text{Var}[\mathbf{y}_{T+h} - \hat{\mathbf{y}}_{T+h|T} \mid \mathbf{y}_1, \dots, \mathbf{y}_T]$ be the covariance matrix of the base forecast errors.
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If \mathbf{SG} is a projection, then trace of \mathbf{V}_h is minimized when $\Psi = \mathbf{W}_h$, so that

$$\mathbf{SG} = \mathbf{S}(\mathbf{S}'\mathbf{W}_h^{-1}\mathbf{S})^{-1}\mathbf{S}'\mathbf{W}_h^{-1}$$

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- MinT is L_2 optimal amongst linear unbiased forecasts.

MinT linear projections

$$\tilde{\mathbf{y}}_{T+h|T} = S\mathbf{G}\hat{\mathbf{y}}_{T+h|T}$$

- How to estimate $\mathbf{W}_h = \text{Var}[\mathbf{y}_{T+h} - \hat{\mathbf{y}}_{T+h|T} \mid \mathbf{y}_1, \dots, \mathbf{y}_T]$?

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Reconc. method $\mathbf{S}\mathbf{G}$

OLS $\mathbf{S}(\mathbf{S}'\mathbf{S})^{-1}\mathbf{S}'$

WLS(var) $\mathbf{S}(\mathbf{S}'\Lambda_v\mathbf{S})^{-1}\mathbf{S}'\Lambda_v$ where $\Lambda_v = \text{diag}(\hat{\mathbf{W}}_1)^{-1}$

WLS(struct) $\mathbf{S}(\mathbf{S}'\Lambda_s\mathbf{S})^{-1}\mathbf{S}'\Lambda_s$ where $\Lambda_s = \text{diag}(\mathbf{S}\mathbf{1})^{-1}$

MinT(sample) $\mathbf{S}(\mathbf{S}'\hat{\mathbf{W}}_1^{-1}\mathbf{S})^{-1}\mathbf{S}'\hat{\mathbf{W}}_1^{-1}$

MinT(shrink) $\mathbf{S}(\mathbf{S}'\hat{\mathbf{W}}_{\text{shr}}^{-1}\mathbf{S})^{-1}\mathbf{S}'\hat{\mathbf{W}}_{\text{shr}}^{-1}$

- $\hat{\mathbf{W}}_{\text{shr}}$ is shrinkage estimator $\tau \text{diag}(\hat{\mathbf{W}}_1) + (1 - \tau)\hat{\mathbf{W}}_1$
where τ selected optimally.

MinT and Geometry papers



SL Wickramasuriya, G Athanasopoulos, and RJ Hyndman (2019). “Optimal Forecast Reconciliation for Hierarchical and Grouped Time Series Through Trace Minimization”. In: *Journal of the American Statistical Association* 114.526, pp. 804–819. URL: <https://doi.org/10.1080/01621459.2018.1448825>.



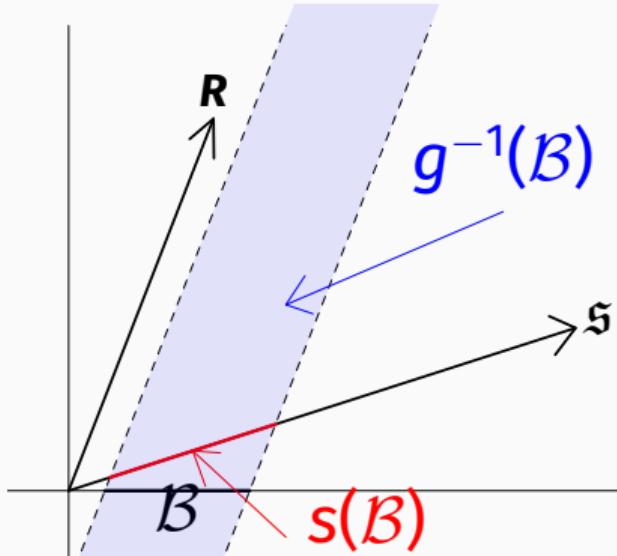
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Probabilistic forecast reconciliation

A probability triple $(\mathfrak{s}, \mathcal{F}_{\mathfrak{s}}, \check{\nu})$ is coherent with the bottom probability triple $(\mathbb{R}^m, \mathcal{F}_{\mathbb{R}^m}, \nu)$, if

$$\check{\nu}(s(\mathcal{B})) = \nu(\mathcal{B}) \quad \forall \mathcal{B} \in \mathcal{F}_{\mathbb{R}^m}$$

- Random draws from coherent distribution must lie on \mathfrak{s} .
- The probability of points not on \mathfrak{s} is zero.
- The reconciled distribution is a transformation of the base forecast distribution that is coherent on \mathfrak{s} .



A Panagiotelis, P Gamakumara, G Athanasopoulos, and RJ Hyndman (2023). “**Probabilistic forecast reconciliation: Properties, evaluation and score optimisation**”. In: *European Journal of Operational Research* 306.2, pp. 693–706. URL: <https://doi.org/10.1016/j.ejor.2022.07.040>

Outline

1

Improving hierarchical forecasts

2

Improving univariate forecasts

3

Improving cross-temporal forecasts

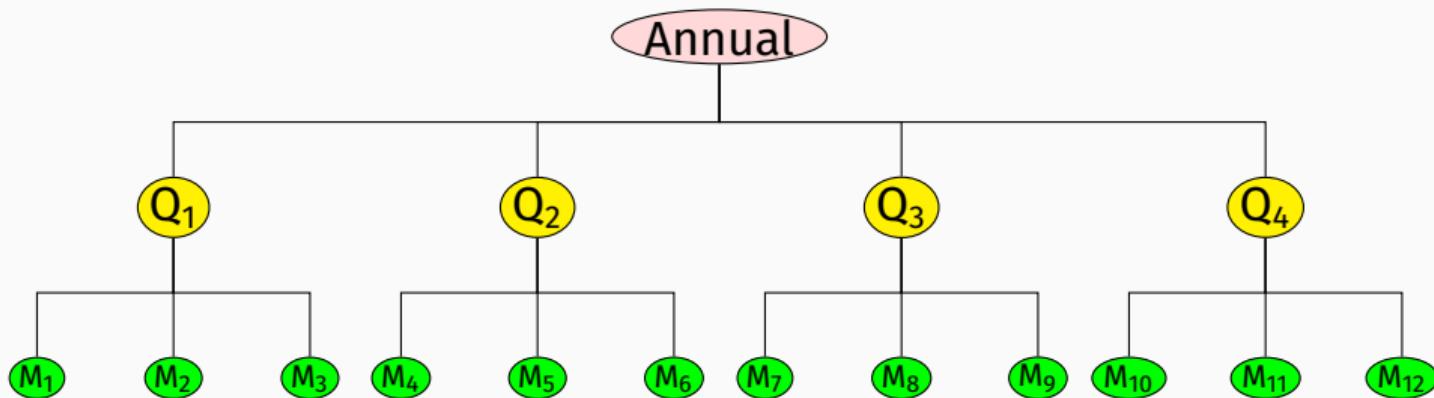
4

Improving multivariate forecasts

5

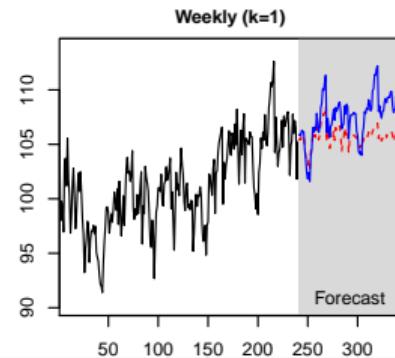
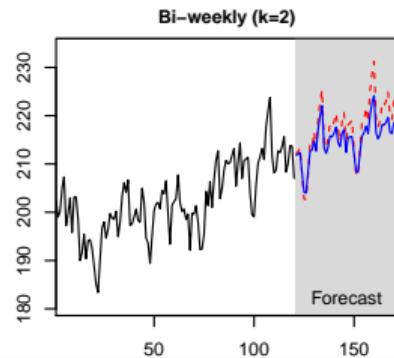
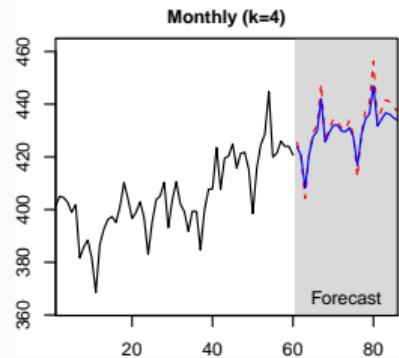
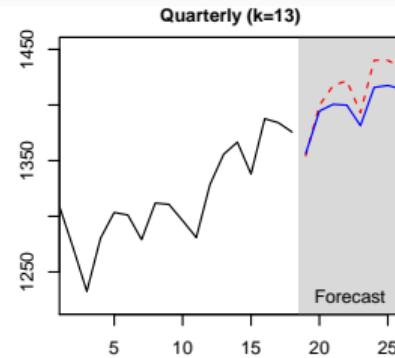
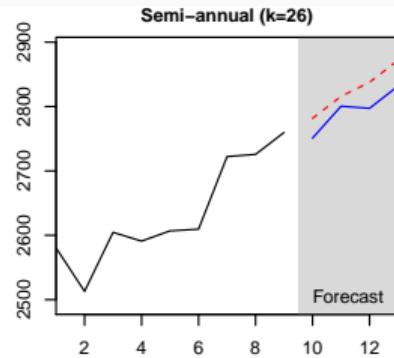
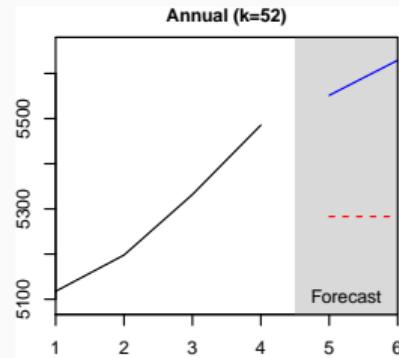
Final comments

Temporal reconciliation: monthly data



- Forecast series at each available frequency.
- Optimally combine forecasts within the same year.

Example: Accident & emergency services demand



Temporal Hierarchical Forecasting - THieF



G Athanasopoulos, RJ Hyndman, N Kourentzes, and F Petropoulos (2017). “**Forecasting with Temporal Hierarchies**”. In: *European Journal of Operational Research* 262, pp. 60–74. URL: <https://doi.org/10.1016/j.ejor.2017.02.046>



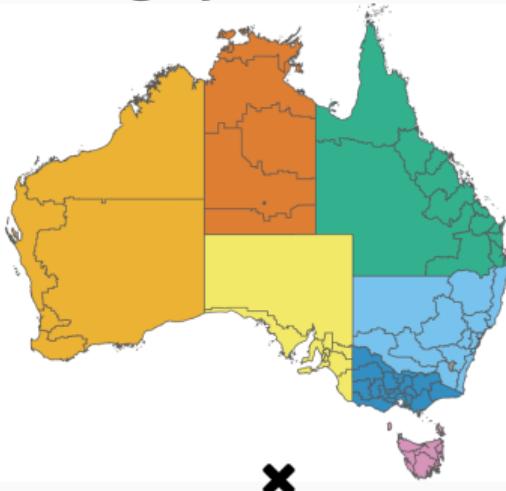
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Cross-temporal reconciliation

Geographical division



Purpose of travel

Holiday, Visiting friends & relatives, Business, Other

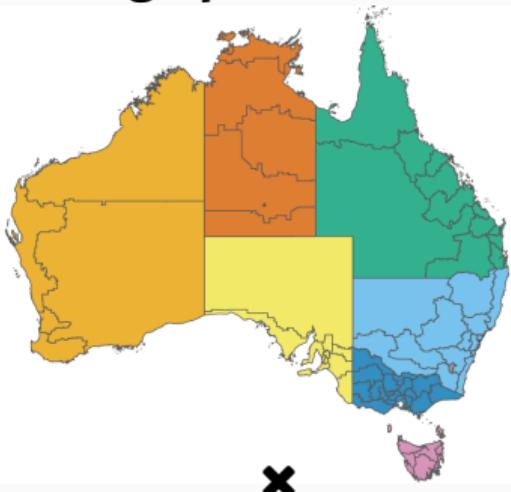
■ Cross-sectional aggregations

(geographical divisions × purpose of travel)

	AUS	States	Zones*	Regions	Tot
geographical	1	7	21	76	105
purpose	4	28	84	304	420
total	5	35	105	380	525

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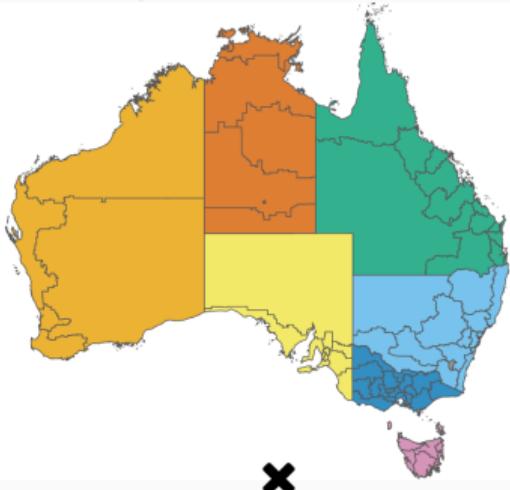
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- ▶ Bi-Monthly
- ▶ Quarterly
- ▶ Four-Monthly
- ▶ Semi-Annual
- ▶ Annual

Cross-temporal reconciliation

Geographical division



Purpose of travel

Holiday, Visiting friends & relatives, Business, Other

Total: 3150 Series

■ Cross-sectional aggregations

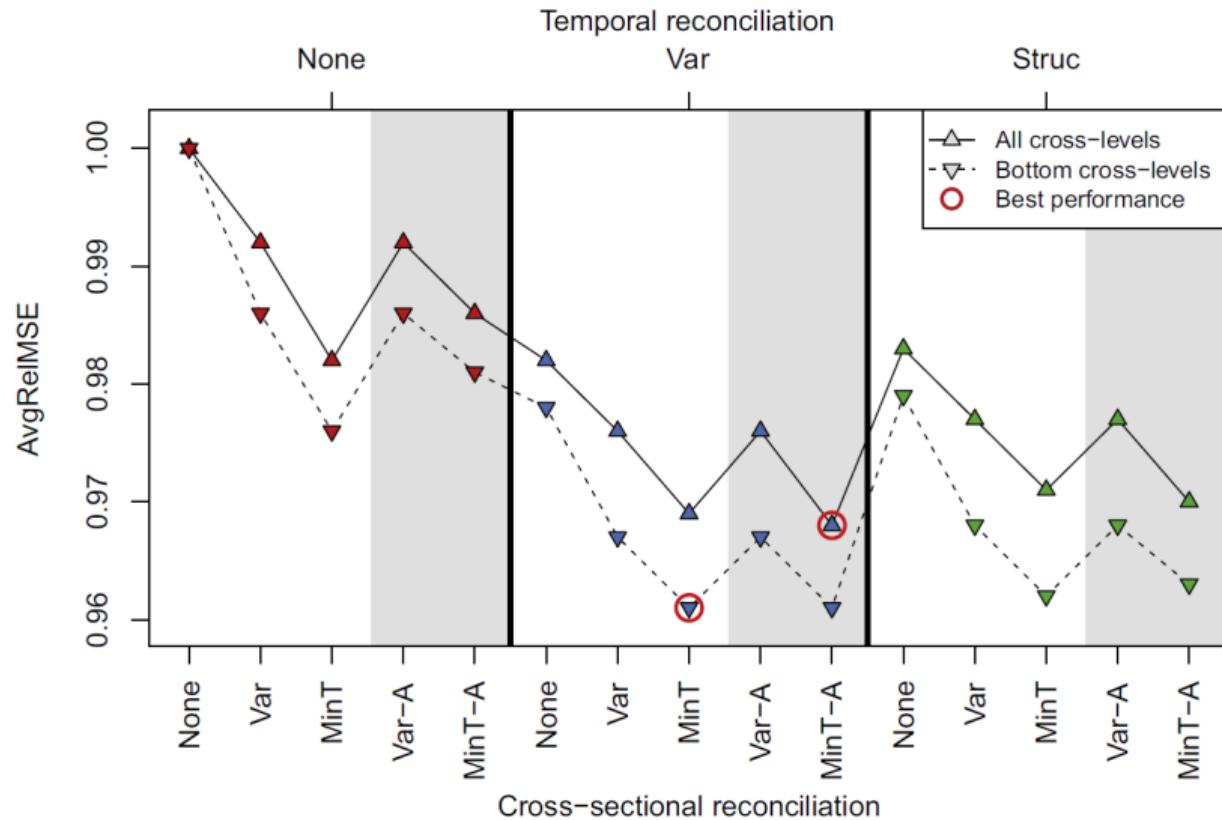
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FLAP (Forecast Linear Augmented Projection)

Intuition:

- Suppose we are interested in multivariate forecasting but do not have linear (or non-linear) constraints.
- Can reconciliation help?

FLAP (Forecast Linear Augmented Projection)

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- Suppose we are interested in multivariate forecasting but do not have linear (or non-linear) constraints.
- Can reconciliation help?

Can we find linear components that:

- 1 are easy to forecast (or easier than the original series);
- 2 can capture possible common signals;
- 3 can improve forecasts of original series.

Outline of FLAP Implementation

- We want to forecast a multivariate series $\mathbf{y}_t \in \mathbb{R}^m$.

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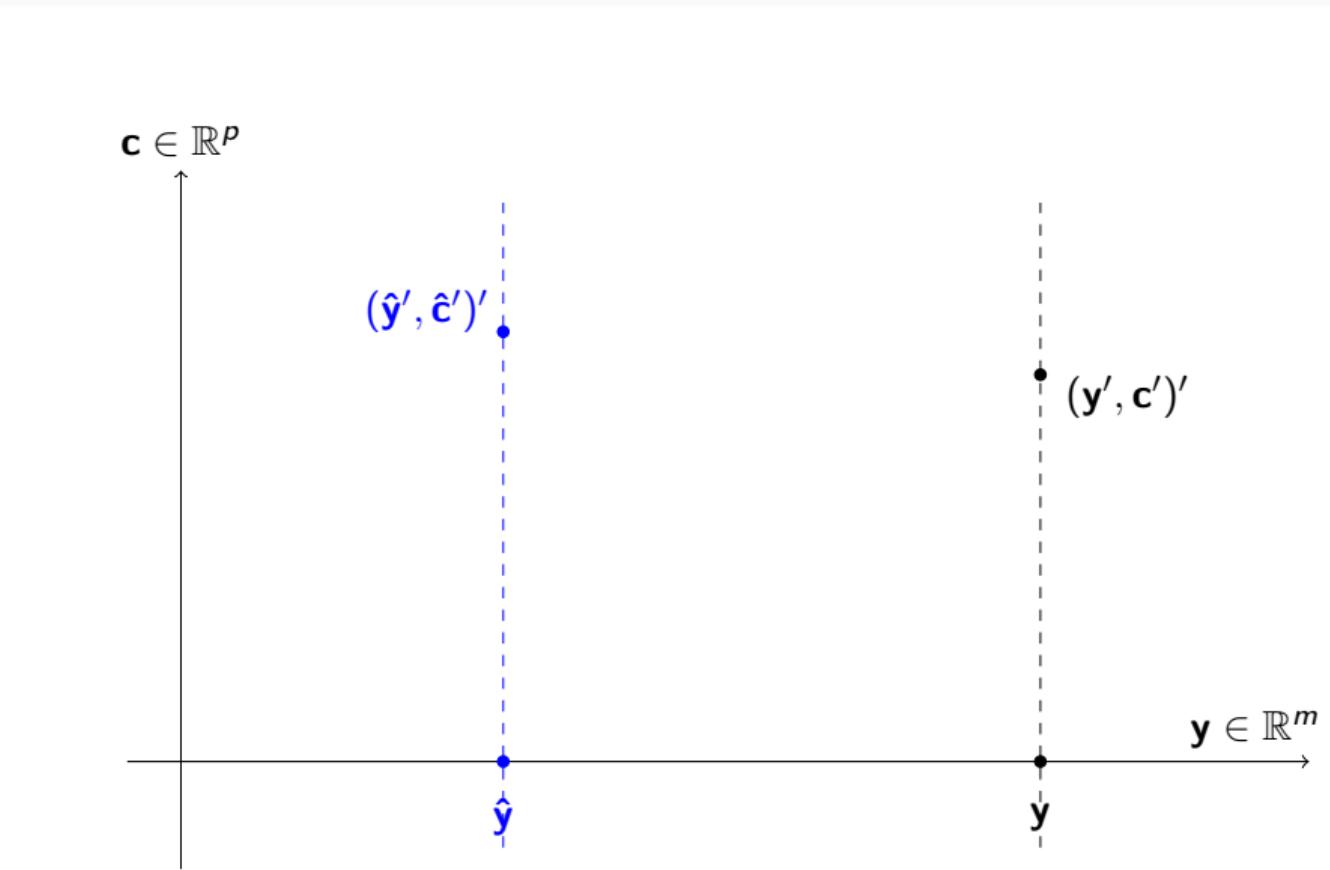
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- Project forecasts onto the \mathbb{R}^m coherent subspace using MinT, resulting in $\tilde{\mathbf{y}}_{t+h}$.

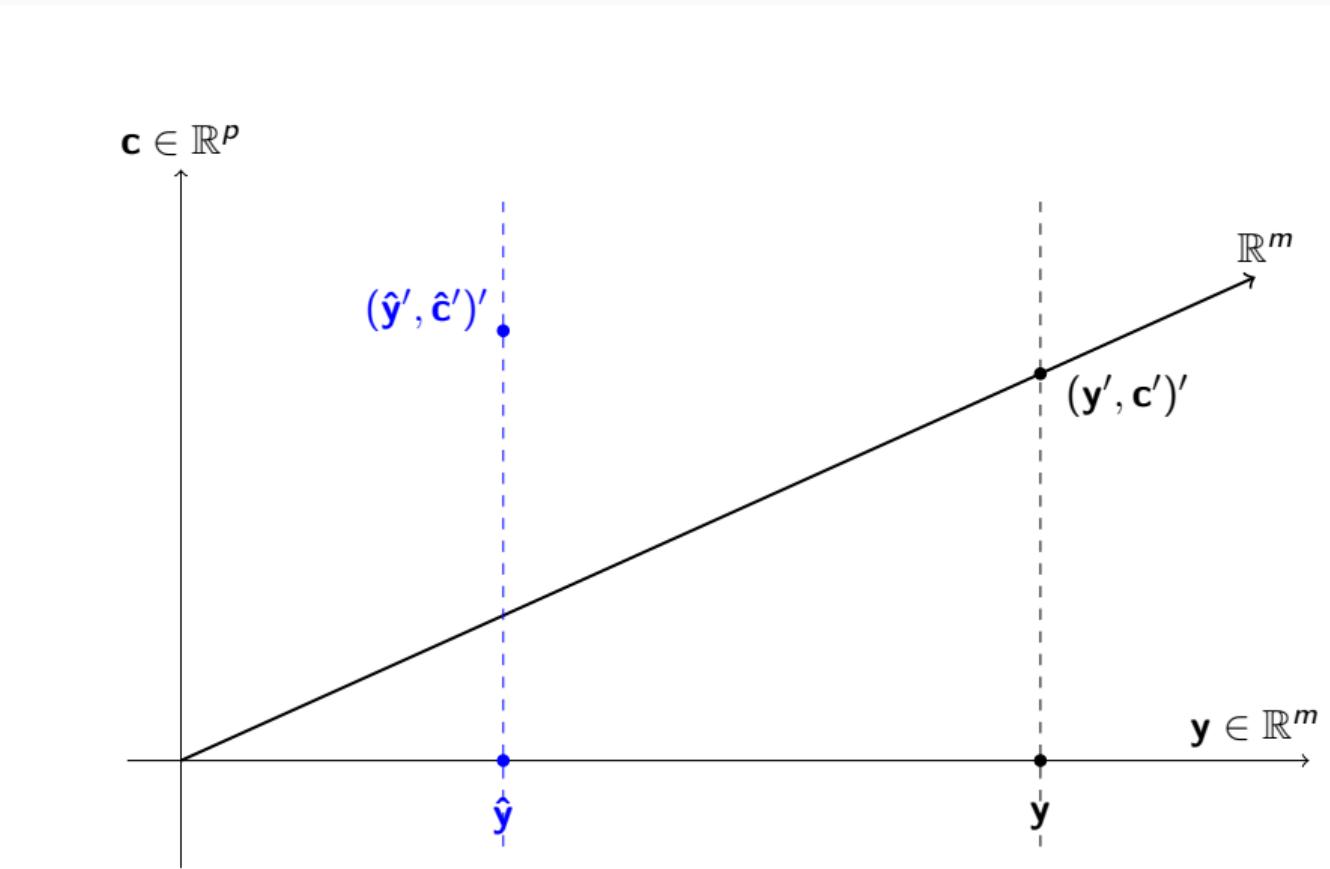
Geometry of FLAP



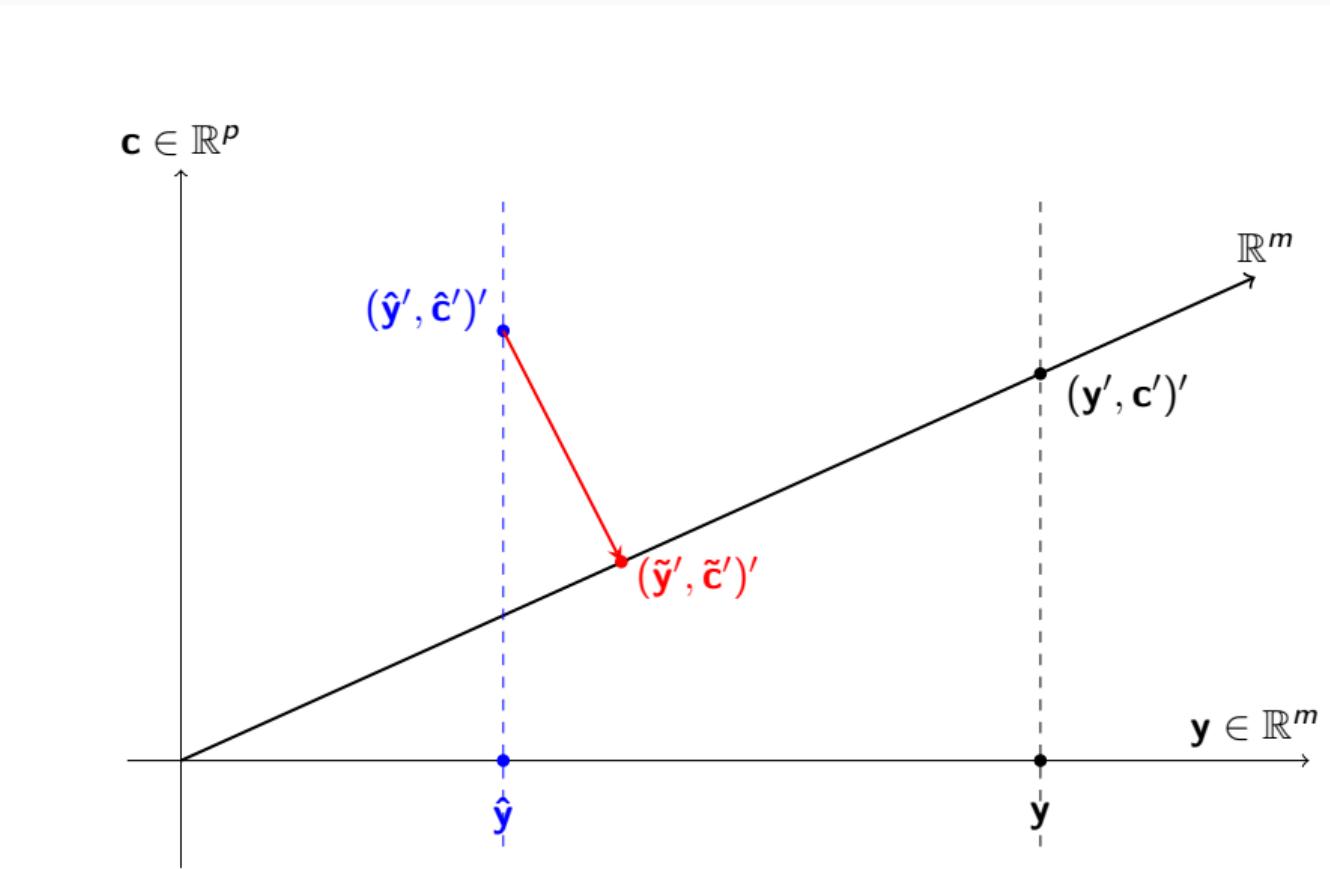
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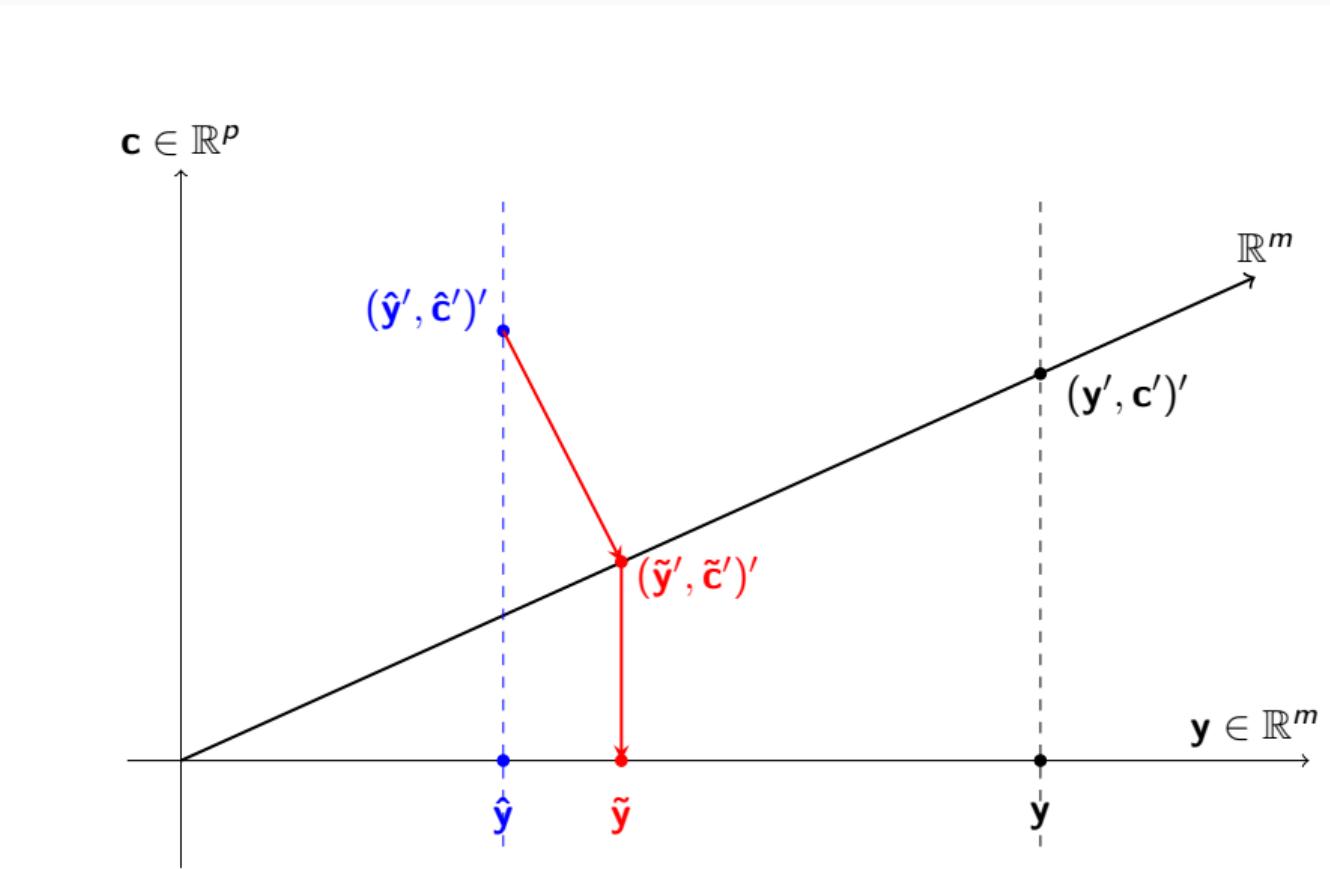
Geometry of FLAP



Geometry of FLAP



Geometry of FLAP



Key results based on MinT

- 1 The forecast error variance is **reduced** with FLAP
 - ▶ $\text{Var}(\mathbf{y}_{t+h} - \hat{\mathbf{y}}_{t+h}) - \text{Var}(\mathbf{y}_{t+h} - \tilde{\mathbf{y}}_{t+h})$ is also **positive semi-definite**.

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- 3 The forecast projection is **optimal** to achieve minimum forecast error variance for each series.

No free lunch

- In practice we need to estimate $\mathbf{W}_h = \text{Var}(\mathbf{z}_{t+h} - \hat{\mathbf{z}}_{t+h})$.
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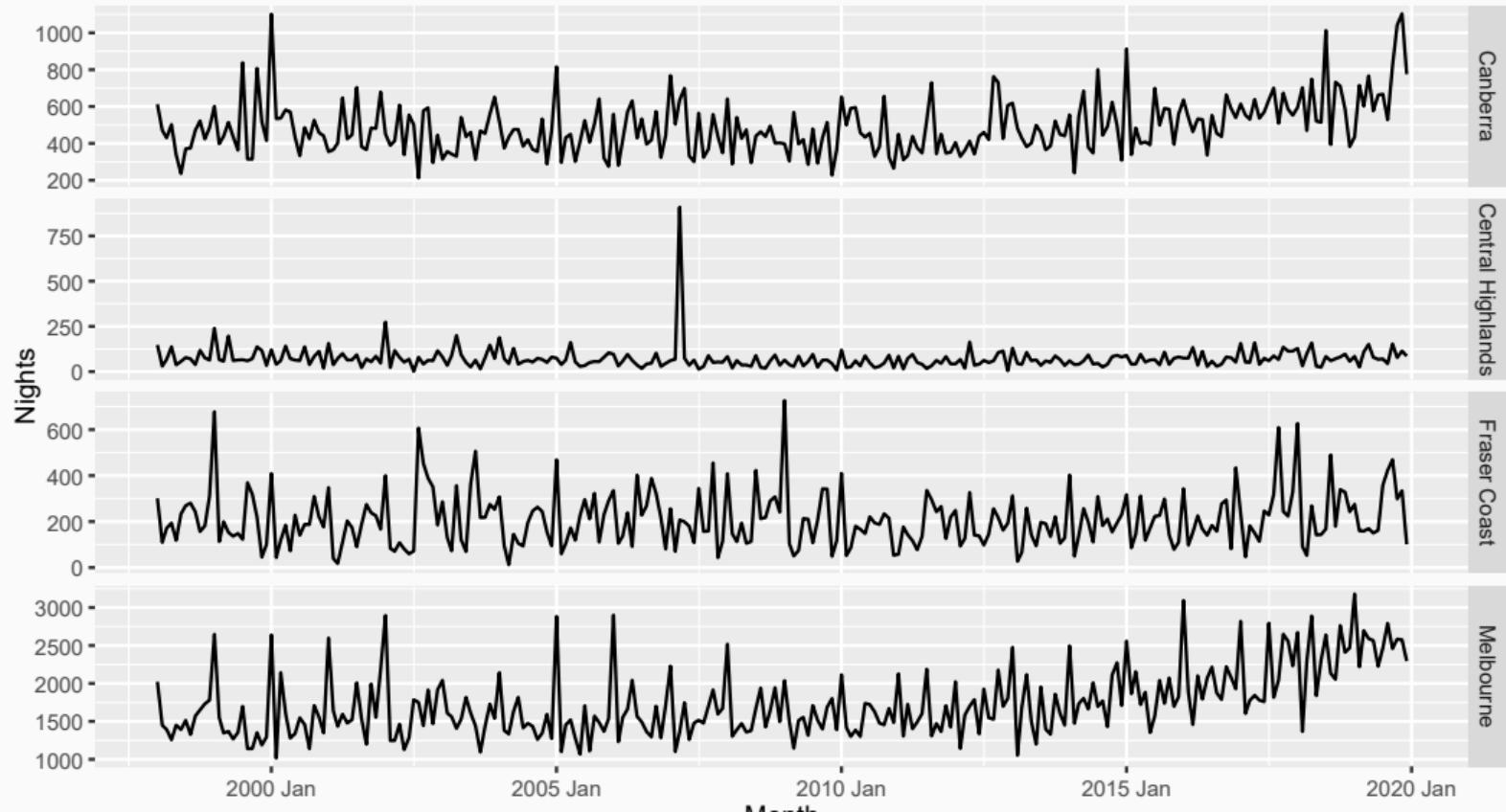
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- The quality of covariance matrix estimates deteriorate with higher dimension.
- However for finite dimension, the benefit of FLAP outweighs errors in estimating covariance matrix.

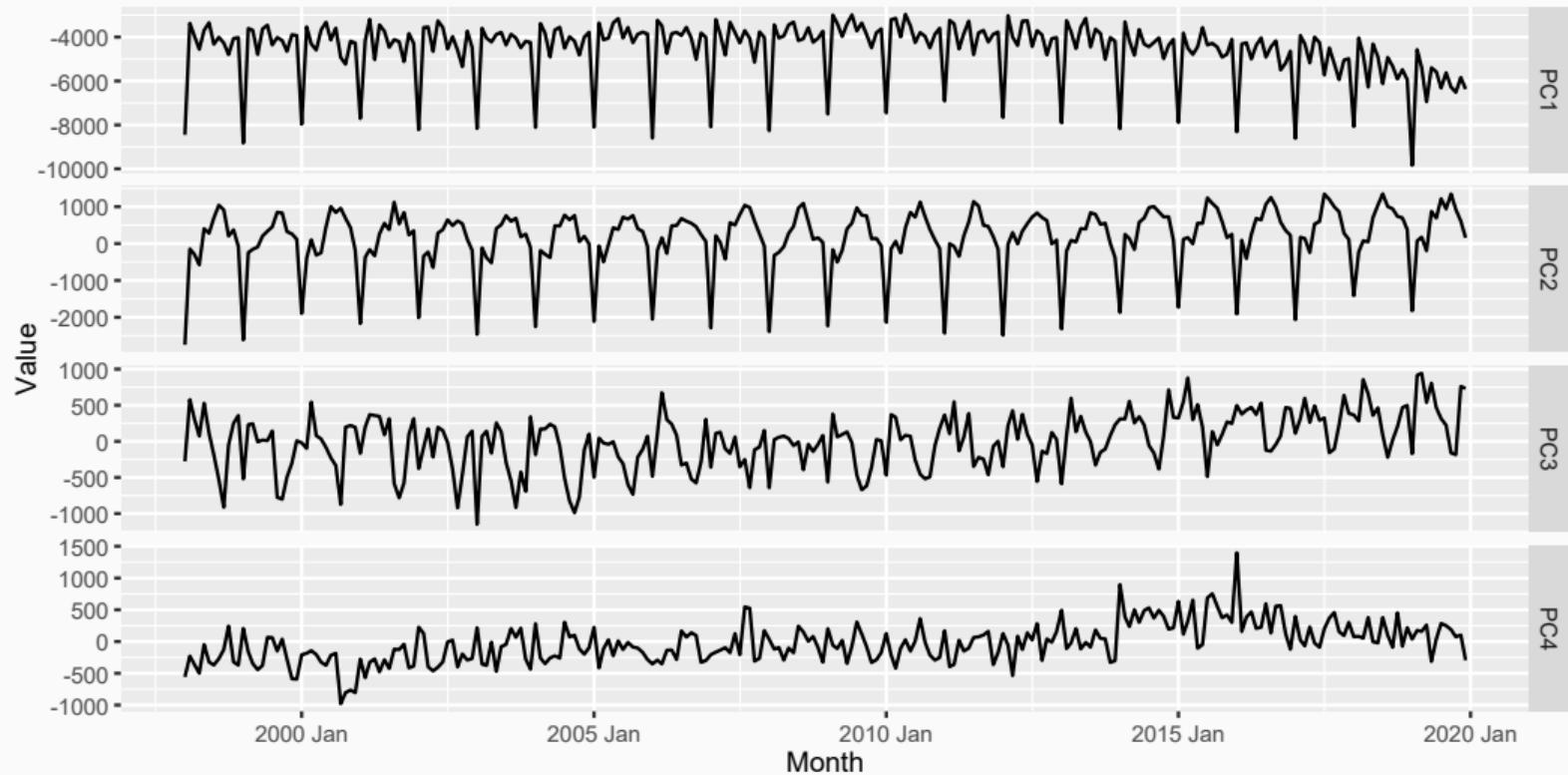
Monthly Australian regional tourism

- Monthly Australian tourism data by region giving 77 series, from Jan 1998 to Dec 2019
- Use expanding window time series cross-validation with $T = 84$ observations in first training set, and forecast horizons $h = 1, 2, \dots, 12$.
- Estimate `ets()` models using the `forecast` package.

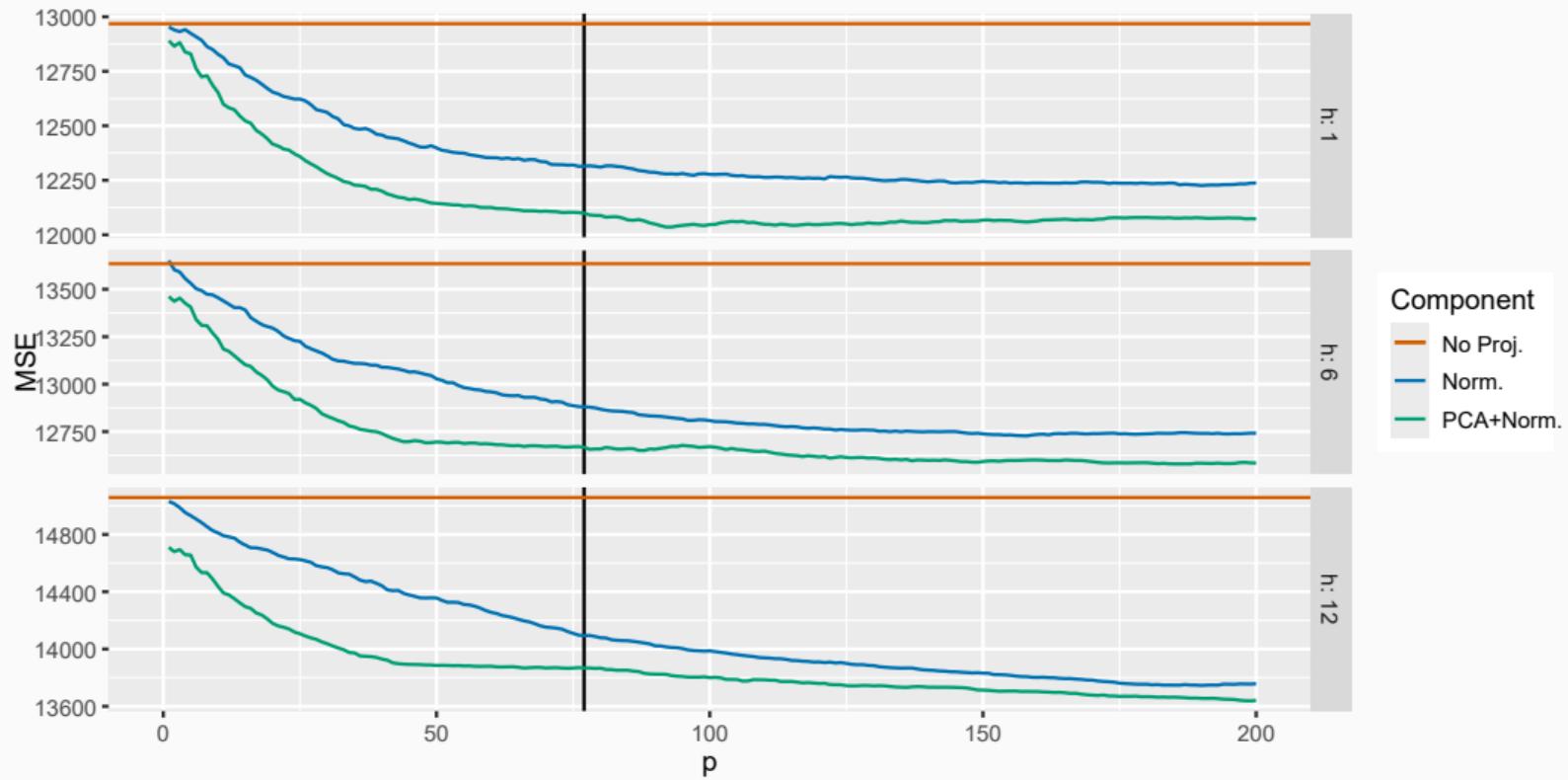
Monthly Australian regional tourism



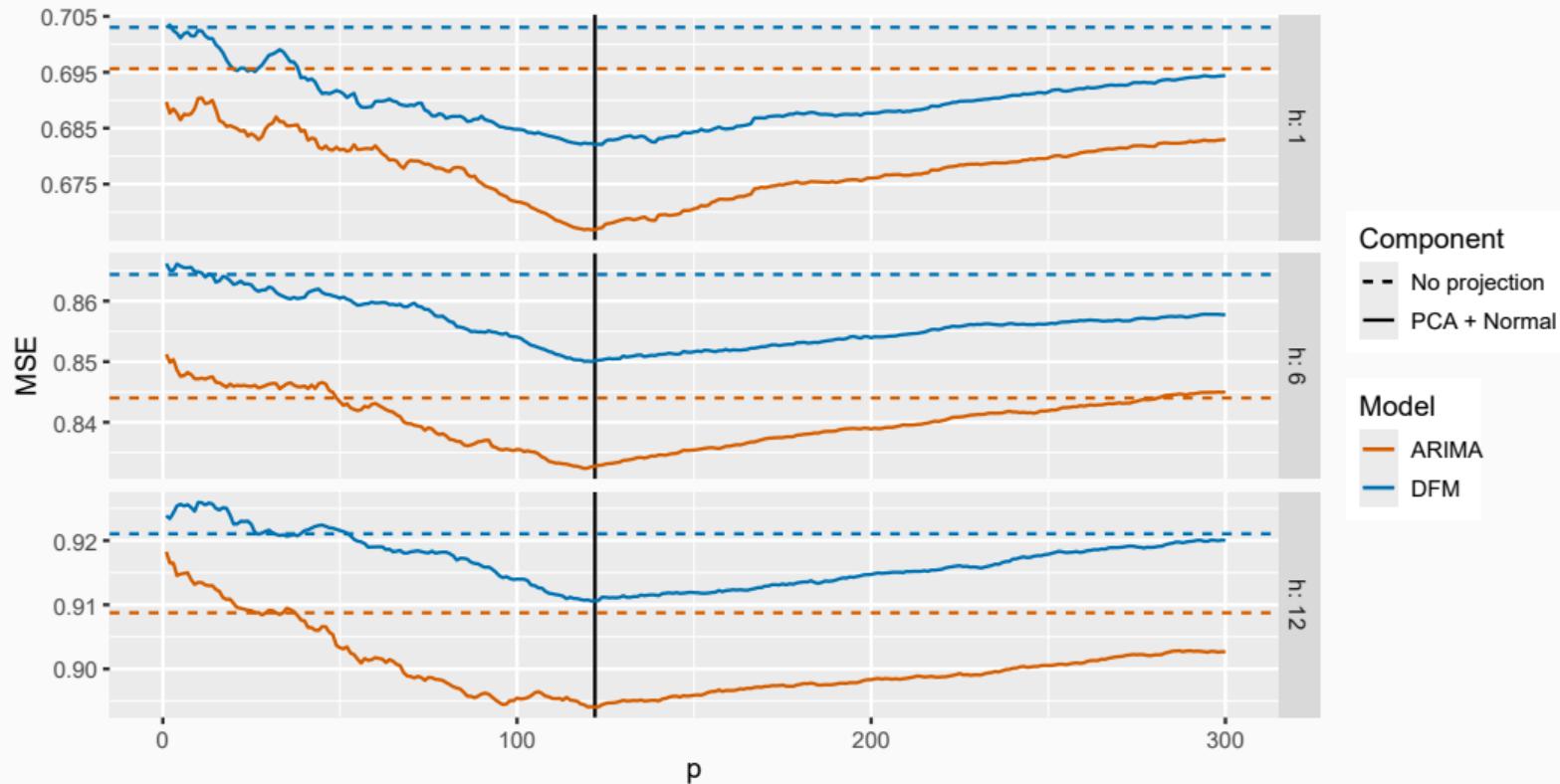
Monthly Australian regional tourism



Monthly Australian regional tourism - ets()



- Monthly data of macroeconomic variables (McCracken and Ng, 2016).
- Data from Jan 1959 – Sep 2023. 777 observations on 122 series.
- Same cleaning process as per McCracken and Ng (2016).
- All series scaled to have mean 0 and variance 1.
- Expanding time series cross-validation with initial size of 25 years and forecast horizon 12 months.



Working Paper and R Package

YF Yang, G Athanasopoulos, RJ Hyndman, and A Panagiotelis (2024). “**Forecast Linear Augmented Projection (FLAP): A free lunch to reduce forecast error variance**”. Department of Econometrics and Business Statistics, Monash University, Working Paper Series 13/24. URL: <https://www.monash.edu/business/ebs/research/publications/ebs/2024/wp13-2024.pdf>

You can install the stable version from CRAN

```
## CRAN.R-project.org/package=flap  
install.packages("flap")
```

or the development version from Github

```
## github.com/FinYang/flap  
# install.packages("remotes")  
remotes::install_github("FinYang/flap")
```

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Links

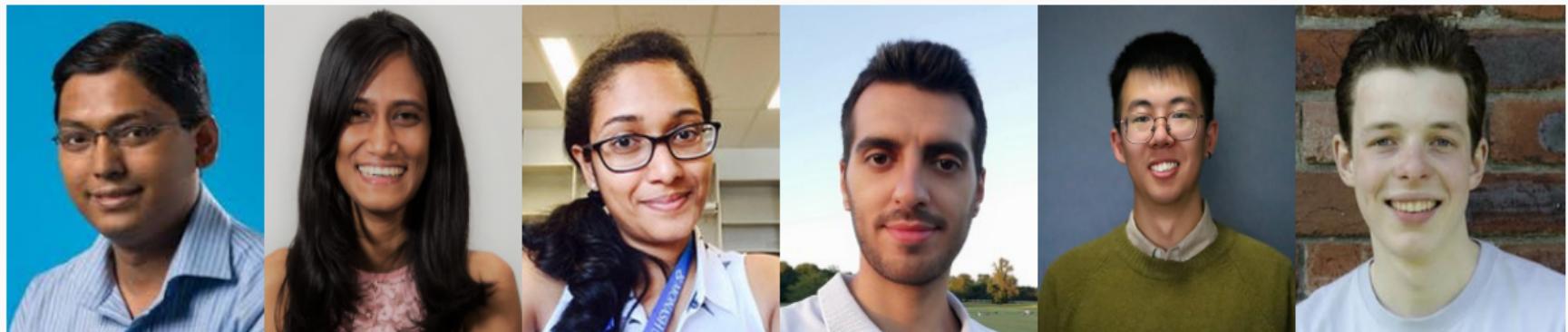


Postdoc opportunity



Link to slides

Thank you to



Other information

Forecasting: Principles and Practice <https://otexts.com/fppgr/>
(Thank you to [Ioannis Nikas](#) and [Athanasios Koutras](#))

Monash webpage

<https://research.monash.edu/en/persons/george-athanasopoulos>

Thank you!

-  Athanasopoulos, G, R Ahmed, and R Hyndman (2009). “**Hierarchical forecasts for Australian domestic tourism**”. In: *International Journal of Forecasting* 25, pp. 146–166. URL: <https://doi.org/10.1016/j.ijforecast.2008.07.004>.
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- Hyndman, RJ, R Ahmed, G Athanasopoulos, and H Shang (2011). “**Optimal combination forecasts for hierarchical time series**”. In: *Computational Statistics & Data Analysis* 55.9, pp. 2579–2589. URL: <https://doi.org/10.1016/j.csda.2011.03.006>.
- Hyndman, RJ and G Athanasopoulos (2021). **Forecasting: principles and practice**. 3nd Edn. Melbourne, Australia. URL: <http://otexts.com/fpp3/>.

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